

Review

Spray and combustion characterization for internal combustion engines using optical measuring techniques – A review

S.N. Soid ^{a,b}, Z.A. Zainal ^{a,*}^a School of Mechanical Engineering, Universiti Sains Malaysia, Engineering Campus, 14300 Nibong Tebal, Penang, Malaysia^b Mechanical Section, Universiti Kuala Lumpur Malaysian Spanish Institute, 09000 Kulim Hi-Tech Park, Kulim, Kedah, Malaysia

ARTICLE INFO

Article history:

Received 7 June 2010

Received in revised form

14 November 2010

Accepted 16 November 2010

Available online 28 December 2010

Keywords:

Spray

Combustion

Visualization

PIV (particle image velocimetry)

PDPA (phase Doppler particle anemometry)

ABSTRACT

The number of studies on spray and combustion characteristics in IC (internal combustion) engines using optical techniques has rapidly increased in the past few years due to an increase in the number of alternative fuels and stricter emission standard regulations. This study investigates better ways of controlling the combustion process, thus ensuring optimum performance and minimum emission levels produced during the combustion process. Alternative fuels such as CNG (compressed natural gas), bio-diesel and hydrogen have been studied by many researchers due to their relative low environmental impact. Meanwhile, for conventional fuels such as gasoline and diesel, studies have focused on spray characteristics to provide better air/fuel mixtures in order to produce a cleaner combustion process. Few experimental works have investigated the effects of modifications to the injector itself, for example, varying the injection rate, injection pressure, etc. In order to provide a better understanding of spray and combustion characteristics, researchers have studied macroscopic and microscopic parameters using optical techniques. This paper presents the significance of spray and combustion study with optical techniques that have been reported by previous researchers in order to provide in depth knowledge as assistance to readers interested in this research area.

© 2010 Elsevier Ltd. All rights reserved.

1. Significant of study on spray and combustion characteristics of IC engine

The fast depletion of fossil fuel resources and their contribution to environmental pollution from ICE (internal combustion engine) are the major issues that led to increasing demand for efficient and eco-friendly energy management schemes to be implemented in industrial, commercial and domestic sectors. One of the feasible ways to tackle the aforesaid problems is to study the macroscopic and microscopic parameters of the fuel spray to ensure high engine performance with low emissions level.

The increasing number of potential alternative fuels also has led to an increase in interest amongst researchers to study spray and combustion characteristics of fuels in engine cylinders using optical methods. Alternative fuels such as biomass, an environmentally clean and renewable energy source, can be mixed with diesel fuel in ICEs [1]. This has been studied by some researchers using optical measuring techniques. Other alternative fuels such as natural gas, hydrogen and oxygenated fuel have also been studied.

For conventional fuels such as gasoline and diesel, emission levels can be reduced by enhancing the spray characteristics and the quality of the air/fuel mixture [2]. It is essential to ensure that all of the injected fuel has maximum contact with the available air to produce complete combustion [3]. Few works have investigated methods of reducing the emissions in ICEs while simultaneously improving the combustion efficiency of the engine. The main techniques that have been used to reduce NO_x and PM (particulate matter) emissions are pulsed injection [4], pilot injection [5,6], HCCI (homogeneous charge compression-ignition) engines [7], control of the mixing process and modification of the injection parameters.

In order to understand the fundamentals of spray and combustion characteristics in ICEs, methods such as visualization, PIV (particle image velocimetry), LIF (laser induced fluorescence) and PDPA (phase Doppler particle anemometry) have been used as diagnostic tools for in-cylinder measurements. These techniques will be reviewed later in this paper. Some measurements have been carried out in modified engines with optical access, and some have been performed in high pressure and temperature CV (constant-volume) vessels. Studies of the fuel spray behavior can be classified into two categories: macroscopic and microscopic. The macroscopic parameters such as the cone angle and tip penetration can be determined through direct

* Corresponding author. Tel.: +60 45996301; fax: +60 5946025.

E-mail address: mezainal@yahoo.com (Z.A. Zainal).

Nomenclature

S	spray tip penetration (m)	T	gas mean temperature ($^{\circ}\text{C}$)
Δp	pressure drop across the nozzle (Pa)	T_w	mean wall temperature
t	time (s)	$dQ_{ht}/d\theta$	rate of heat transfer out of the system (W)
d_n	nozzle diameter (m)	l	distance (m)
ρ_g	gas density (kg/m^3)	P_{flu}	fluorescence signal
ρ_l	liquid density (kg/m^3)	η_c	detection efficiency of the collection system
T_g	gas temperature (K)	Ω	solid angle of collection optics (sr)
$U_s(t)$	instantaneous spray tip velocity (m/s)	V_c	collection volume (m^3)
D_{SM}	Sauter mean diameter (m)	f_l	fractional population of the lower electronic state
D_d	droplet diameter (m)	x_m	mole fraction of the absorbing species
dn	number of droplets	N	total number density of the gas molecule (m^{-3})
$dQ_{ch}/d\theta$	apparent rate of chemical energy or heat release ($\text{J}/^{\circ}$)	I_{v0}	spectral intensity of incident laser light ($\text{Wm}^{-2}\text{Hz}^{-1}$)
θ	crank angle ($^{\circ}$)	A_{21}	Einstein coefficient for spontaneous emissions
γ	ratio of specific heat at constant pressure and volume	Q_{21}	collisional transfer coefficient, encompassing all forms of collisions
p	in-cylinder pressure (Pa)	B_{12}	Einstein coefficient for stimulated absorption
V	cylinder volume (m^3)	I_0	low laser intensity
		I_{sat}	saturation laser intensity

visualization methods [8]. Meanwhile, the microscopic parameters such as velocity, scalar field and droplet size can be measured using either PIV or PDPA techniques. It is well known that the efficiency of combustion relies heavily on the quality of the air/fuel mixture, which is dependent on the fuel injection into the combustion chamber. Ideally, all of the injected fuel should be in contact with the maximum amount of available oxygen, to ensure that the combustion of the hydrocarbons can be as complete as possible [9]. In the present study, a comprehensive survey was carried out in the area of spray and combustion using optical measuring technique and presented from the history up to the current stage.

1.1. History

Since 1970s, many researchers focused on the spray and combustion characteristics of various types of fuel. Few review papers have been published in the late 70s and in the early 80s on the fuel droplet size measurement techniques [10,11]. A review by Chigier [12] gives an outline of atomization and burning of liquid fuel sprays.

In 1980s, the technique that was used in droplet size measurement can be classified into three classes which are mechanical, electrical and optical methods. One of the earliest works that was published on the flame propagation through an air-fuel spray mixture with transient droplet vaporization in a closed combustor was reported by Seth et al. [13] in 1980. While in 1981, Banhaw and Whitelaw [14] had experimentally studied the interaction between fuel spray and surrounding combustion air at different degree of air swirl. In 1982, laser tomographic light scattering technique was used by Yule et al. [15] to study the turbulent kerosene sprays under cold and vaporization in hot surrounding air streams. The vapor/liquid visualization in fuel sprays was studied by Melton and Verdieck using exciplex visualization system in 1985. While in 1991, one of the earliest studies on fuel spray using laser Doppler system was done by Nakabe et al. [16] in studying the detailed flame structure of liquid fuel sprays. The phase/Doppler technique was also used by Presser et al. [17] to study the fuel property effects on the structure of spray flames. While in 1994, Senda et al. [18] had used visualization and exciplex fluorescence technique to study the fuel vapor concentration in diesel spray.

Over the last 40 years, the techniques have evolved to become more sophisticated and detailed with important information obtained from the fuel spray that makes optimization of the spray parameters possible to researchers.

1.2. Macroscopic spray parameters

The typical spray structure of a DI (direct-injection) fuel spray is shown in Fig. 1 [19], where the fuel is introduced into the engine cylinder through a nozzle. As the liquid jet leaves the nozzle, it becomes turbulent and the outer surface of the jet breaks up into droplets. In turbulent mixing processes, the turbulent eddies formed in the shear layer will engulf the surrounding fluid in the jet core, and mixing subsequently takes place on the molecular level at the two-fluid interface [20], thus making the transport phenomenon of the fluid motion the dominant process in turbulent mixing. Study of the turbulent transport of the jet fluid will directly determine the distribution of the jet fluid concentration and its vortex motion [21]. As one move away from the nozzle, the mass of air within the spray increases, the spray diverges, its width increases, and the velocity decreases. The fuel droplets evaporate as this air-entrainment process proceeds. The tip of the spray penetrates further as the injection proceeds at a decreasing rate.

The region of spray tip penetration becomes longer and wider as the ambient air temperature increases, due to the lower in-cylinder gas density at higher temperatures [22]. The longer tip penetration and larger cone angle are desirable for maximum air utilization and better combustion due to the increased spray area. In some engine

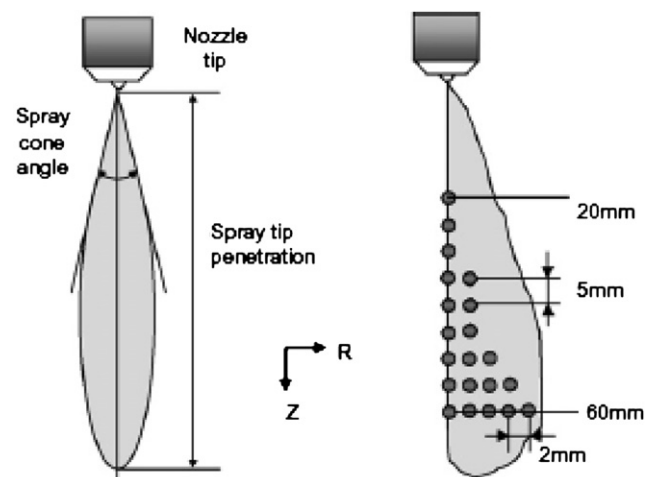


Fig. 1. The definition of macroscopic spray characteristics by Suh et al. [19].

designs in which the walls are hot and high air swirling is present, fuel impingement on the walls is desirable. However, in multi-spray DI diesel combustion systems, with little or no air swirling, over-penetration results in impingement of liquid fuel on cool surfaces, which lowers the mixing rates and increases the emissions of the unburned and partially burned species. The spray tip penetration can be calculated by the formula developed by Dent [23] as shown in equation (1), below;

$$S = 3.07 \left(\frac{\Delta p}{\rho_g} \right)^{1/4} (td_n)^{1/2} \left(\frac{294}{T_g} \right)^{1/4} \quad (1)$$

Further detailed studies have examined the spray tip location as a function of time, and Hiroyasu and Arai [24] correlated their data for spray tip penetration, S as below;

$$t < t_{break} \quad S = 0.39 \left(\frac{2\Delta p}{\rho_l} \right)^{1/2} t \quad (2)$$

$$t > t_{break} \quad S = 2.95 \left(\frac{\Delta p}{\rho_g} \right)^{1/4} (d_n t)^{1/2} \quad (3)$$

$$\text{where} \quad t_{break} = \frac{29\rho_l d_n}{(\rho_g \Delta p)^{1/2}} \quad (4)$$

The instantaneous spray tip velocity can be calculated as shown in equation (5), below;

$$U_s(t) = \frac{1}{2} \frac{S}{t} \quad (5)$$

For jets in the atomization regime, the spray cone angle θ was found using equation (6).

$$\tan \frac{\theta}{2} = \frac{1}{A} 4\pi \left(\frac{\rho_g}{\rho_l} \right)^{1/2} \frac{\sqrt{3}}{6} \quad (6)$$

Finally, using the equations (1) and (6), the projected spray area and volume of the fuel jet can be calculated.

The injection rates of the fuels can be measured and analyzed using an injection rate measuring system based on the Bosch method [25], in which the pressure variation in a tube is monitored as the fuel is injected into the tube.

1.3. Microscopic spray parameters

The atomization regime is determined by the diesel engine injection conditions, where the fuel jet is generally in the form of a cone spray and produces much smaller droplets in comparison with the nozzle exit diameter. However, at low jet velocities, the droplet size is larger than the nozzle diameter, due to the unstable growth of surface waves caused by surface tension. The further increment in jet velocity leads to a breakup in the atomization regime of the jet outer surface at or before the nozzle exit plane, creating droplets with an average diameter that is much smaller than the nozzle diameter. Atomization of the liquid fuel into a large number of small droplets is required to create a large surface area for the fuel to evaporate.

During the injection period, the droplet size distribution at a given location may vary not only with time but also with injection conditions, such as the difference in droplet size at the spray core and spray edge, trajectories of individual droplets and the initial velocity due to the atomization process. In order to characterize the spray, expressions for droplet size distribution and mean diameter

are required; the latter can be represented by the Sauter mean diameter [26] as shown in equation (7).

$$D_{SM} = \left(\int D_d^3 dn \right) / \left(\int D_d^2 dn \right) \quad (7)$$

After the atomization process, spray evaporation of the jet fuel is essential before it can be mixed with air. There are three phenomena involved in the droplet evaporation process: deceleration of the droplet due to aerodynamic drag, heat transfer to the droplet from the air and mass transfer away from the droplet by vaporization. As the droplet comes into contact with hot air inside the combustion chamber, the fuel vapor pressure and evaporation rate will increase due to heat transfer from the air. The vaporization process of the spray is very important as it will affect the ignition stability and flame propagation.

Few studies have been conducted investigating the structure of non-evaporative and evaporative sprays. In non-evaporative transient sprays, the inner structure is regularly spaced and branched [27]. The spacing between the branches is in the order of a few millimeters, and it is nearly constant throughout the injection period. Meanwhile, Kosaka and Kamimoto [28] investigated the spray structure of an evaporating spray using SSI (silicone particle scattering imaging). The remaining silicone oil droplets in the evaporating spray represent the fuel vapor concentration. It was found that the silicone oil remained un-evaporated at a temperature of 640 K and that the evaporating spray at higher temperatures has a structure that differs from that of non-evaporating sprays.

Yuyama et al. [29] developed a novel entropy analysis method based on statistical thermodynamics. Entropy analysis can define the degree of homogeneity in the fuel concentration. The high concentration of the liquid-phase distribution tip occurs at the wall of the combustion chamber before evaporation, thus leading to a high possibility of emissions of unburned hydrocarbon. Therefore, a high degree of homogeneity is desired in engine combustion, as it will produce more complete combustion and reduce engine emissions.

1.4. Combustion characteristics

The fundamental step of the combustion process in SI (spark-ignition) engines begins with the fuel and air mixing and being induced into the combustion chamber through the intake valve. At the end of the compression stroke, the combustion is initiated by an electric discharge at the spark plug. The turbulent flame develops and propagates inside the combustion chamber and is then extinguished at the end of the power stroke.

Meanwhile, the difference between CI (compression-ignition) engines and SI engines lies in their compression ratios, where the compression ratio of CI engines is much higher, in the range of 12–24, to allow for self-ignition of the diesel fuel. The valve timings used in CI engines are similar to those of SI engines. The air at close-to-atmospheric pressure is induced during the intake stroke and then compressed to a pressure of about 4 MPa and a temperature of about 800 K during the compression stroke. Fuel injection into the engine cylinder starts at about 20° before the TC (top center).

The liquid fuel jet atomizes into droplets and evaporates inside the engine combustion chamber and then mixes with air within the combustible limit. Within a short period, the air temperature and pressure rise above the fuel's ignition point. After a short delay period, spontaneous ignition of the fuel/air mixture initiates the combustion process, and the cylinder pressure rises above the non-firing engine level. The flame spreads rapidly through the portion of injected fuel that has already mixed with sufficient air for burning. As the expansion process proceeds, mixing between fuel, air and burning gases continues, accompanied by further combustion.

An important engine combustion diagnostic measurement is the in-cylinder pressure trace. Using this pressure measurement, considerable information about the nature of the combustion process under any operating condition can be collected. A typical in-cylinder pressure diagram for SI and CI engines is shown in Fig. 2, from Zainal and Soid [30]. Using the in-cylinder diagram, the most important information can be obtained by performing a so-called heat release analysis. This analysis will reveal the rate of mass burned and the volume fraction engulfed by the flame as functions of the crank angle. For SI engines, the chemical energy or gross heat release rate can be calculated using equation (8).

$$\frac{dQ_{ch}}{d\theta} = \frac{\gamma}{\gamma-1} p \frac{dV}{d\theta} + \frac{1}{\gamma-1} V \frac{dp}{d\theta} + V_{cr} \left[\frac{T'}{T_w} + \frac{T}{T_w(\gamma-1)} + \frac{1}{bT_w} \ln \left(\frac{\gamma-1}{\gamma'-1} \right) \frac{dp}{d\theta} + \frac{dQ_{ht}}{d\theta} \right] \quad (8)$$

For CI engine operation, the heat release rate [31] is given by equation (9). A typical heat release diagram for CI engine operation is shown in Fig. 3.

$$\frac{dQ_n}{dt} = \frac{\gamma}{\gamma-1} p \frac{dV}{dt} + \frac{1}{\gamma-1} V \frac{dp}{dt} \quad (9)$$

In diesel engines, the ignition delay is defined as the time interval between the SOI (start of injection) and the SOC (start of combustion). The ignition delay occurs because both physical and chemical processes must take place before a significant fraction of chemical energy of the injected fuel is released. The start of the fuel injection is usually determined by a “needle-lift indicator” which traces the movement of the injector needle with respect to crank angle. The SOC can be determined in several ways such as the point where firing pressure exceeds motoring pressure or where heat release begins or maybe when the first visible light from combustion is observed. The duration of this ignition delay period is especially important in diesel combustion since it affects both the performance and emissions. The net heat release rate during this period usually turns out to be negative due to the heat losses to the cylinder walls and the fuel vaporization.

In premixed or rapid combustion phase, the fuel and air that are mixed and prepared during the ignition delay period burn rapidly, leading to high heat release rates and rapid cylinder pressure rise. Since the amount of fuel and air are mixed within the flammability limits depends on the duration of the ignition delay period, the longer the ignition delay, the more prepared fuel-air mixture with higher initial heat release rates and pressure rise. Thus in order to avoid excessive heat release rates and to keep rates of pressure rise acceptable, the ignition delay period should be as short as possible.

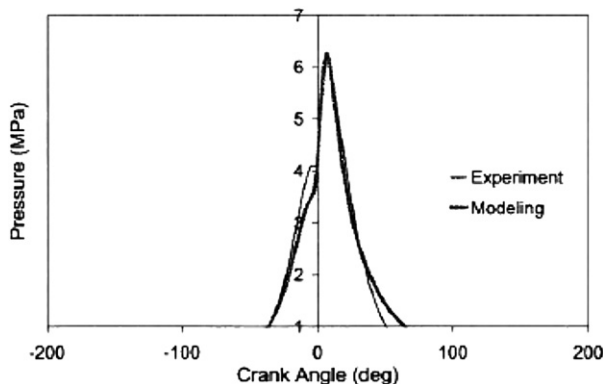


Fig. 2. In-cylinder pressure comparison between experiment and modeling at 2400 rpm and 30% of brake power by Zainal and Soid [30].

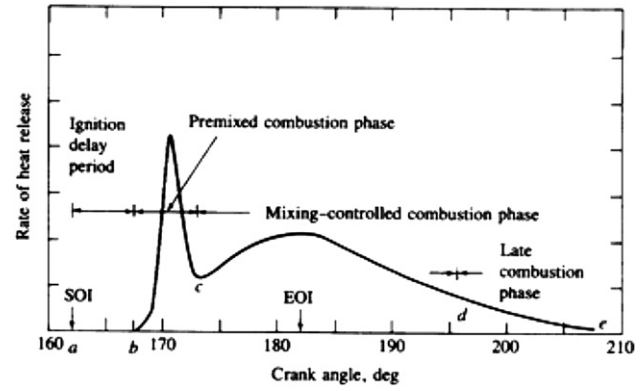


Fig. 3. Phases in Diesel Engine Combustion Process by Heywood [26].

After the “premixed” fuel-air mixture has been burned, the rate of combustion in mixing-controlled combustion phase is controlled by the rate at which fuel-air mixture becomes available for burning which is largely dependent on the fuel injection rate and fuel vapor-air mixing rates. The heat release in this phase is typically of a lower magnitude and occurs over a much longer duration compared to the rapid combustion phase. This is because the fuel-air mixing time scales are much higher than the chemical reaction time scales. As the injected fuel continues to burn, the piston expands and the heat release rate decreases.

Late combustion phase is characterized by very low heat release rates due to the combustion of the remaining fuel, CO and soot. This phase is usually terminated by the temperature drop during expansion which slows down the kinetics of the final burning.

1.5. Conventional techniques

Previously, the technique that was used in droplet size measurement can be classified into three classes which are mechanical method (droplet capture, cascade impaction, frozen drop and wax methods and sedimentation technique), electrical methods (Wicks–Dukler technique, the charged wire probe and the hot wire anemometer) and optical method (photography, holography, laser diffraction, laser anemometry and various other techniques based on light scattering). However there is not much information obtained for the conventional technique, except for the large scale model.

Palopski [32] had used a large scale model to study the spray characteristics of fuel such as the droplet size and velocity. The nozzle size used was larger than the normal size causing a decrease in the droplet velocity and increase in droplet size. Walzel [33] had also used large scale models in spray formation studies and small scale models for black liquor nozzles of recovery boilers and heavy oil nozzles of blast furnaces that was used in splash plate nozzle studies. More work using large scale models have been used by Soteriou et al. [34] to study the fuel flow inside the diesel nozzle. However, the used of large scale model only helped in understanding the break up and atomization mechanism but might be inaccurate for diesel spray characteristics as proven by Rantanen et al. [35].

2. Optical techniques

Optical techniques are commonly used for macroscopic and microscopic fuel spray and combustion characterization. However, these techniques can often be difficult to implement and very expensive. According to Roisman et al. [36] the spray, especially in the neighborhood of the nozzle, is very dense; making the use of optical measurement techniques very difficult. Some examples of

optical techniques are visualization, PIV, LIF and PDPA. The visualization technique has been reviewed by Chigier [37], while the optical measurement techniques such as LIF have been reviewed previously by Zhao and Ladommatos [38].

2.1. Visualization technique

The most frequently used optical measurement technique for macroscopic characteristic of fuel spray measurement is the direct visualization method. The visualization of digital imaging either in solid state or continuous recording can be employed to expose the conditions of the spray and the combustion process. The macroscopic parameter such as spray geometry, penetration depth, wall impingement, and subsequent combustion can be exposed using this technique. For the purpose of simulating the actual spray and the combustion process in IC engines, a high pressure and temperature CV vessel can be used as the combustion chamber, and shadowgraph photos of the fuel spray and the combustion process can be acquired using a high-speed digital camera. The typical experimental setup for visualization technique was shown in Fig. 4.

2.1.1. Spray and combustion characterization using visualization

2.1.1.1. Spray and combustion characteristics. Diesel spray injection and combustion was studied by Bougie et al. [39] in a high pressure and temperature cell. As a novelty, they had observed quasi-simultaneous imaging of spray propagation and combustion using two ICCD (intensified charge-couple device) cameras with double framing options. Two dimensional flash light shadowgraph, laser elastic scattering and chemiluminescence were used to investigate the fuel propagation, and laser-induced incandescence was used to study the soot formation. The analysis shows the fuel vapor cloud extending well beyond the liquid core and close to the nozzle tip. The ignition also takes place close to the spray tip and soot is formed in the vapor core region at the tip. The characteristics of an evaporating diesel spray and the flame distribution in the combustion chamber of a DI diesel engine also was investigated by Yoshizaki et al. [40].

The macroscopic diesel fuel spray was studied by Klein-Douwel et al. [41] using high-speed digital imaging in a high pressure cell to provide a better and more fundamental understanding of the interaction between the fuel injection and the spray propagation. In

this work, they had presented the experiment and the algorithm for geometrical analysis and explain the way to determine the local spray angle, cone angle and spray penetration.

The flame structures of wall-impinging diesel sprays injected by group-hole nozzles were investigated by Gao et al. [42] in a CV combustion vessel, as shown in Fig. 5. It was found that an asymmetric flame structure emerged in wall-impinging group-hole nozzle sprays. Group-hole nozzles, with a large included angle, yield a higher overall OH chemiluminescence intensity. The wider the flame, the greater the proportion of high OH intensity, thus providing better fuel/air mixing and improving the combustion process.

Kostas et al. [43] experimentally studied the initial stages of diesel fuel spray development in a CV vessel. The fuel spray was observed for a duration of 0.5 ms after the SOI using an ultra-high speed camera. It was found that the tip penetration shows linear dependencies at the initial stages of spray development. Moreover, the spray tip velocity was found not to be constant, but proportional to $\sqrt{t}$.

Nishida et al. [44] investigated the mixture formation process of sprays injected from a two-hole nozzle for DISI (direct-injection spark-ignition) engines, aimed to achieve better air utilization, using the LAS (laser absorption-scattering) technique. Their results showed that, as the HAA (hole-axis angle) of the nozzle decreased, the droplet coalescence increased and the vapor mass decreased. The tip penetration also increased with decreasing HAA. Additionally, an increased injection pressure significantly increases the vaporization rate and the tip penetration rate.

The characteristics of spontaneous ignition and combustion with unsteady high-speed gases such as natural gas and hydrogen fuel jets were investigated by Ishiyama et al. [45] using visualization methods in a CV vessel as shown in Fig. 6. The fundamental data of engine combustion that was fueled by natural gas and hydrogen were observed in order to determine a method for controlling the combustion. It was found that a higher temperature is needed for natural gas ignition, and for hydrogen fuel, the ignition delay is shorter, as compared to natural gas.

The spray and combustion characteristics of DME (dimethyl ether) were experimentally studied by Wakai et al. [46] using a CV vessel at 3.1 MPa and 823 K. It was found that the DME spray was ignited 2.6 ms after the SOI, with the first ignition occurring around the middle portion of the spray and the flame spreading in the downstream direction. Further observation showed that the flame was non-luminous and that light emission from the flame was very weak. Under lower ambient pressures (2.1 and 1.1 MPa), the ignition delay of the DME spray was shorter than that of a diesel fuel spray, whereas it was almost the same as the diesel fuel delay at higher ambient pressures (4.1 and 3.1 MPa). Moreover, at an ambient pressure of 1.1 MPa, the DME spray could be ignited at temperatures >770 K, in contrast to the diesel fuel, which could not be ignited.

Bang and Lee [47] had studied the fuel injection characteristics and spray behavior of biodiesel blended with methyl ester using visualization technique. The experiments were conducted at various blending ratio; B25, B50 and B75 fuels. From the analysis it was found that a shorter injection delay, shorter injection duration and higher peak value of injection rate was noted by lower blending ratio. The spray penetration analysis also shows the blended fuel has a similar spray length at the same condition except for the neat DME fuel. It was also found that the DME evaporated more rapidly, but a wider cone angle was observed when biodiesel and blended fuels were tested.

The spray properties of different blends of ethanol-gasoline (25%, 50%, 75% and 100% ethanol) was studied by Gao et al. [48] under various ambient conditions using high-speed schlieren

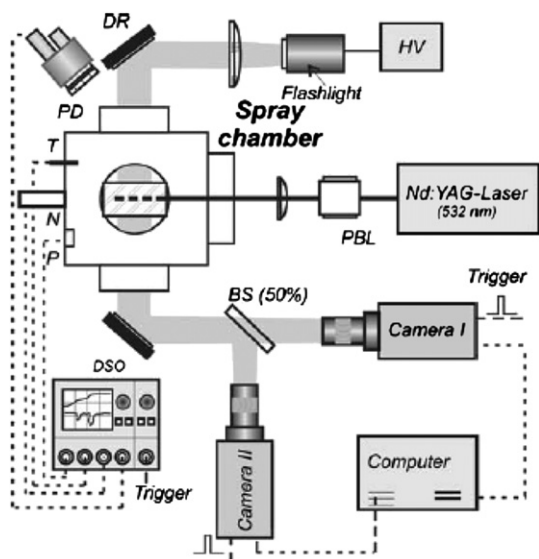


Fig. 4. Visualization setup used by Bougie et al. [39].

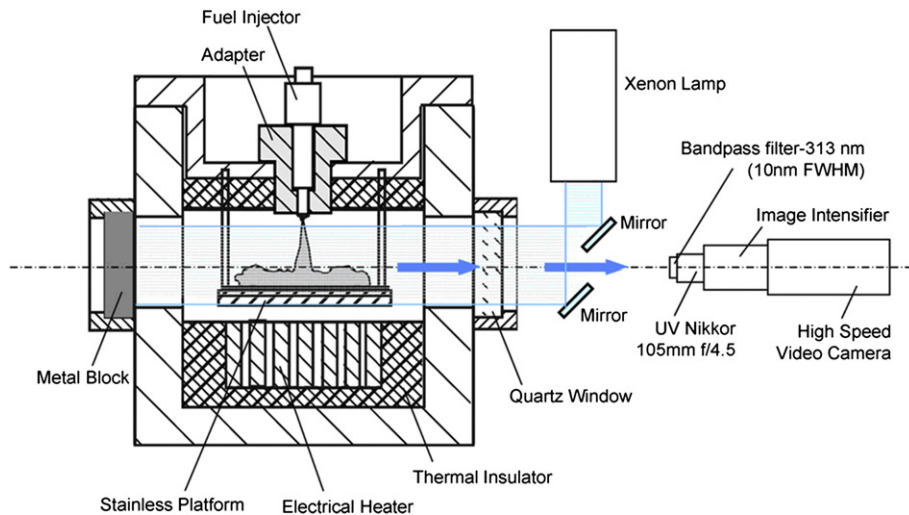


Fig. 5. Schematic of the constant-volume combustion vessel and optical setup for direct flame and OH chemiluminescence imaging used by Gao et al. [42].

photography technique. From the analysis, the similar spray pattern was observed for both blended fuel and pure gasoline. At low ambient pressure, there is better evaporation with the increase of ethanol fraction, indicated by the decrease of tip penetration and increase in spray angle. However, at elevated pressure, there is no difference in spray penetration among the blends. Moreover, the spray angle for all blends was kept almost constant in the fully developed stage.

The influences of different injection strategies and biodiesel blends on the spray and combustion development were studied by Fang et al. [49] in an optical HSDI (high-speed direct-injection) engine. In order to investigate the effect of different injection strategies, three injection timings were chosen to the four diesel/biodiesel blends that are pure European low sulfur diesel (B0), 20% (by volume) soybean biodiesel mixed with 80% low sulfur diesel (B20), 50% soybean biodiesel mixed with 50% low sulfur diesel (B50), and pure soybean biodiesel (B100). It was found that the heat release rate of biodiesel is dominated by premixed combustion and that the heat release peak decreases with a slower injection timing. Combustion analysis also showed that the ignition and heat release rate peak occur later with increasing biodiesel content. Visualization of the combustion process also showed that stronger fuel impingement and a longer tip penetration were produced with increasing biodiesel content. An extension work on biodiesel was done by Fang et al. [50] on the effects of advanced injection strategies and NO_x emissions using the same optical HSDI engine.

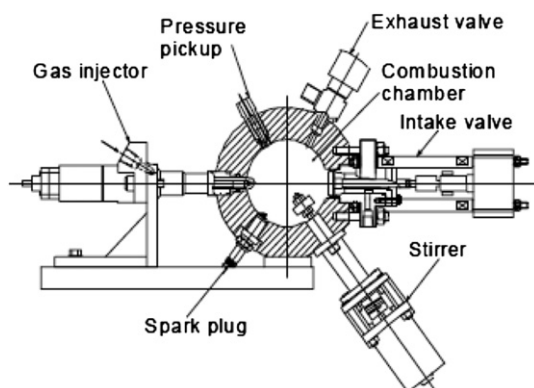


Fig. 6. Constant Volume Vessel used by Ishiyama et al. [45].

Desantes et al. [51] had studied the macroscopic injection parameters of three biodiesel blends on DI diesel-injection using a standard injection system derived from a 4-Stroke diesel engine. The experiments were carried out over a commercial diesel fuel, with 5.75% of RME (rape methyl ester) categorized as B5, another with 30% of RME (B30), and a pure RME fuel. The analysis was done on the injection rate shape, spray force, spray tip penetration and cone angle in non-evaporative conditions. It was found that the fuel property such as density of the fuel highly affects the injection parameters. Higher viscosity of the RME makes the injector needle lift slower thus resulted in longer penetration, narrower cone angle and smaller spray volume.

An extension work on RME fuel was done by Pastor et al. [52] to study the liquid-phase fuel penetration, soot luminosity measurements and time-resolved intensified imaging to detect apparition of CH and OH chemiluminescence and early soot radiations. The liquid-phase fuel penetration and soot luminosity were measured using high-speed imaging, and the chemiluminescences of both CH and OH have been observed using intensified imaging. From the analysis, it was found that the fuel penetration increases linearly with blending rates (RME longest, 30% of RME medium and 5% of RME was the shortest). The chemiluminescence of CH found led to a decrease of ignition delay by about 50 μ s for an increase of RME blend rate. Moreover, the high-speed imaging of OH chemiluminescence shows that the RME rate did not show any significant influence, as this parameter is controlled by physics rather than by chemistry.

There were two studies done on the combustion near the valves regions. The fuel deposition burning in PFI (ported fuel injection) in SI engine was studied by Merola and Vaglieco [53] to investigate the diffusion-controlled flame to evaluate the flame propagation and the chemical species involved during the combustion. Morela et al. [54] had also studied on the effect of the fuel injection strategy using the same rig. Single and double fuel strategies with two injection pressures were investigated to study the diffusion-controlled flames in valves region and on the cylinder wall.

2.1.1.2. Effect of nozzle parameters. Payri et al. [55] investigated the effect of cavitation on the internal flow and macroscopic spray characteristics in a diesel-injection nozzle using visualization methods. In this work, two bi-orifice nozzles were used, which were cylindrical and convergent (conical). In order to avoid obscuring the windows, nozzles with two orifices were used and the injector is positioned so that the sprays are situated perpendicular to the

camera and flash window. This also allows a characterization of each spray to be made without interferences from others. It was found that cavitation leads to an increment of the spray cone angle. Based on internal flow analysis, when cavitation is initiated, the whole outlet velocity increases due to a reduction in the cross section of the liquid phase in the outlet section of the hole. The structure and evolution of cavitation and its influence on jet patterns were previously studied by Ganippa et al. [56]. More work on the effect of nozzle cavitations of diesel and biodiesel fuels was done by Suh et al. [57] and they had found that the cavitation of biodiesel fuel would occur at a higher cavitation number.

The impact of injection pressure was investigated by Delacourt et al. [58] using digital imaging techniques. As pressure is one of the most important parameters, the spray characteristics at very high pressures (up to 250 MPa) were evaluated. For the experimental setup, images of the spray development were captured using a fast video camera under direct lighting. In this work, spray characteristics such as cone angle, spray area and tip penetration were observed (Fig. 7). The impact of ultra-high injection pressure (up to 300 MPa) of biodiesels on spray characteristics was also investigated by Wang et al. [59].

The effects of orifice diameter on a diesel fuel jet flame were investigated by Pickett and Siebers [60] in a CV combustion vessel. The orifice diameters were varied from 45 μm to 180 μm , and it was found that, with decreasing orifice diameter, the lift-off length (the farthest upstream location of high-temperature combustion) decreases, but the estimated amount of air entrained increases, thus resulting in an overall average equivalence ratio decrease in the initial combustion zone. The total soot incandescence significantly decreases as the orifice diameter decreases, indicating that a smaller amount of soot is formed relative to the amount of fuel injected. Moreover, the normalized flame length appears to decrease as the orifice diameter increases.

The effect of the diesel nozzle geometry on spray liquid-phase fuel penetration in evaporative conditions was investigated by Payri et al. [61] using visualization methods. Three six-hole sac nozzles used differ in the orifice degree of conicities and were characterized geometrically and hydraulically were used. The liquid-phase fuel penetration in an evaporative environment was also measured. It was found that the velocity and mass flow rate were strongly influenced by cavitation, but the momentum flux was not influenced by the appearance or development of cavitation. Based on a LL (liquid length) analysis, in general, for a given temperature, a shorter LL means faster and better air/fuel mixing. An extension work on the effect of nozzle geometry was done by Payri et al. [62] and focused on the CH and OH chemiluminescence techniques to examine the combustion process.

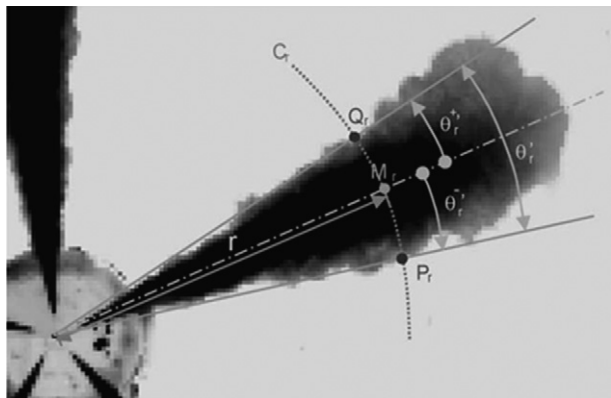


Fig. 7. Spray angle calculation θ (the negative of the image) by Delacourt et al. [58].

Meanwhile, the effects of the injection angle on the combustion processes of HSDI diesel engines were studied by Fang et al. [63] using an optical engine. In this work, two different injectors, with 70-degree and 150-degree tips were used. It was found that the heat release patterns were different for both injectors. Fuel wall impingement was found on the 70-degree tip on the first injection. The 150-degree tip produced a weak flame for the first injection, but the 70-degree tip produced two types of flames: an early weak flame and a late luminous film combustion flame. The spray patterns for 70-degree and 150-degree tips are shown in Fig. 8.

2.1.1.3. Fuel injection system. A swirling injector was also studied by Moon et al. [64] using visualization methods. In this work, they had used an extended tiny probe (0.6 mm outer diameter and an inner diameter of 0.4 mm) to measure the static pressure inside the spray and along the nozzle axis. The visualization of spray shows that the extended probe can access up to 0.5 mm from the nozzle without disturbing the spray shape. In order to obtain the macroscopic spray development under different operating conditions, Mie-scattered spray images were obtained using a laser sheet formed by a 6 Wcw Ar-ion laser, a cylindrical lens with focal length 6.5 mm, and a plano-convex lens with a focal length of 1000 mm. A CCD (charge coupled device) camera (PCO Inc. Sencicam) was utilized with a resolution of 1280×1024 pixels with an exposure time of 10 μs . It was found that the air pressure drop was greater at higher injection pressures. The air pressure at the nozzle exit also showed a higher value at higher fuel temperatures. Moreover, the pressure drop at high fuel temperatures was greater than that of atmospheric temperature. Further downstream, the reduced air pressure returned to atmospheric pressure.

2.1.1.4. Cyclic variations in IC engine. Wang et al. [65] studied the cyclic variations of DI combustion of natural gas hydrogen blends using visualization methods in a CV vessel. Flame propagation photographs and pressure data were acquired at various hydrogen volumetric fractions in the fuel blend. In order to study the effect of cyclic variations, the authors repeated 50 combustion experiments under the same initial condition for various hydrogen fraction fuel blends and equivalence ratios of 0.6 and 0.8. The amount of data can provide the analysis of cyclic variations using CV vessel. It was found that cyclic variations were initiated at the early stages of flame development. The addition of hydrogen caused a flame kernel that was nearly concentric with the spark electrode. Moreover, an increase in the hydrogen fraction decreased the cyclic variation.

2.1.1.5. Engine emission. Kitamura et al. [66] studied NO_x control in DI PCCI combustion with a CV vessel using n-heptane that was injected into the combustion chamber using a single-hole nozzle. In order to obtain the NO_x ($\text{NO} + \text{NO}_2$) concentration, the collected gas

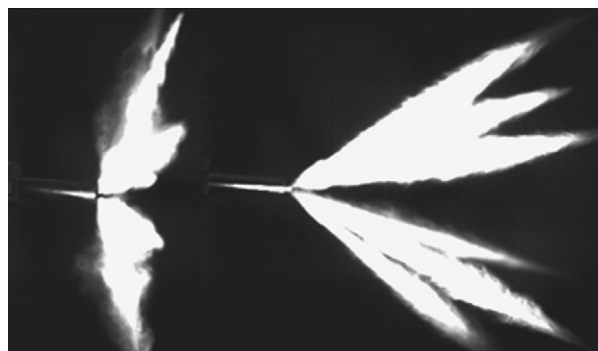


Fig. 8. Spray in quiescent air for the 150-degree (left) and 70-degree (right) injector tips by Fang et al. [63].

was then analyzed using a chemiluminescence NO_x analyzer (YANACO ECL-88A). It was found that enhanced fuel/air mixing reduced NO_x accompanied by a delayed hot flame, and under low oxygen mole fraction conditions, a lower heat release rate was obtained. Based on the analysis of a fixed nozzle orifice diameter, the final NO_x emission was reduced with increasing injection pressure. It was concluded that the enhancement of fuel/air mixing reduces the final NO_x emissions, but when the quantity of the injected fuel exceeds a certain level, the injection conditions have only a slight effect on the final NO_x emissions. The shadowgraph images and pressure history are shown in Fig. 9.

2.2. Particle image velocimetry (PIV) technique

The experimental arrangements for PIV measurements are shown in Fig. 10. PIV is a measurement technique for obtaining the instantaneous whole field velocities. The PIV will measure the distance traveled by particles in the flow within a known time interval. These particles are known as seeding particles. The seeding particles are added to follow the flow, and in order to detect their movement, an area of the flow is illuminated by a light sheet that can be generated by a double pulses laser and optical system. To detect the position of the illuminated seeding particles, a CCD camera is located at right angles to the light sheet. The particle position will appear as light specks on a dark background on each camera frame. The pulsing light sheet and camera are synchronized so that the particle position at the light pulse number one is obtained at frame number one and particle position from pulse number two is on frame number two.

The images are divided into rectangular regions, known as interrogation areas. The interrogation areas from each frame are

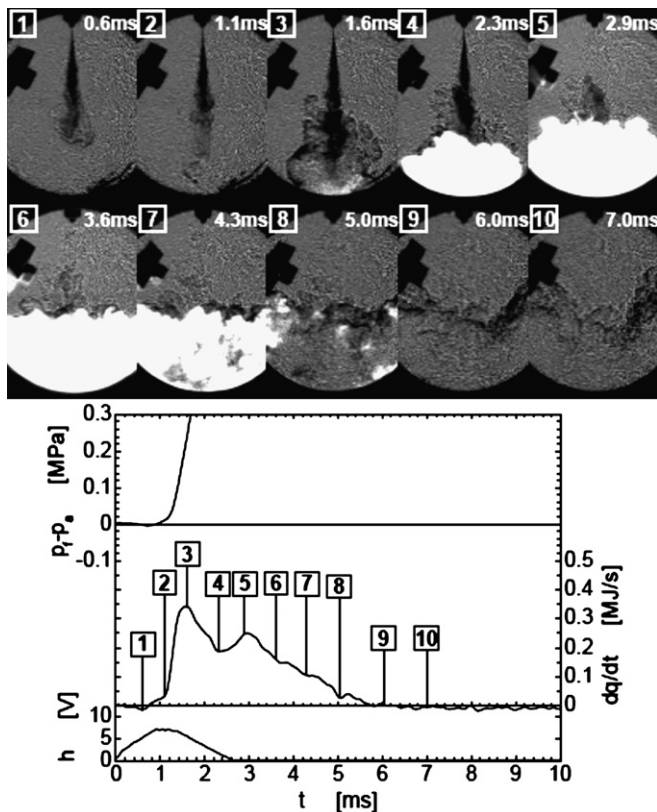


Fig. 9. Shadowgraph images and pressure history under the simulated diesel condition (Ambient condition: $p_i = 4$ MPa, $T_i = 900\text{K}$, $r_{O_2} = 21\%$, Injection condition: $dN = 0.18$ mm, $p_{inj} = 120$ MPa, $m_f = 19.5$ mg) by Kitamura et al. [66].

correlated to produce an average particle displacement vector to produce a vector map of average particle displacements and the displacement vectors are converted into a map of so-called raw velocity vectors. More information about PIV can be found in a report by Kompenhans and Kähler [68].

2.2.1. Spray characterization using PIV

2.2.1.1. *Turbulent premixed flame.* Stella et al. [69] had studied three-component PIV (Fig. 11) measurements in a turbulent premixed flame. As the conventional PIV allows the measurement of the in-plane components of the velocity, the stereoscopic PIV configuration also yields the out of plane components. In this work, stereoscopic PIV technique was used to investigate the turbulence jet flame. Using the stereoscopic PIV, the availability of planar three components velocity fields significantly enhanced the capability of inferring three-dimensional flows in a correct and detailed manner. Three-component planar velocity fields (2D3C) were measured using a stereoscopic PIV system. Two recording cameras were used to observe the motion of seeding particles from different directions. From the third component, these two cameras recorded different apparent particle displacements. The premixed jet flames were produced with a laboratory burner and the mixing between the fuel (propane) and air was injected from four orthogonal orifices. From the analysis, it was found that the stereoscopic PIV technique was capable of measuring three-component planar velocity fields that associated with topological information on the instantaneous reacting surface, deduced by the distribution of seeding particle density in the recording image. This technique is very effective for turbulent combustion process investigation.

2.2.1.2. *Spray behavior and distribution.* Lee et al. [67] experimentally studied the spray behavior and fuel distribution of GDI (gasoline direct-injection) injectors using entropy analysis and PIV methods. Their results showed that the fuel spray propagates more widely in the downstream direction. The entropies of the whole area of the spray are higher when the ambient temperature is higher than the fuel evaporation temperature. The spray of the large injector attached angle is distributed at the center of the cylinder, as compared to the small injector attached angle. Moreover, the droplets are concentrated near the injector tip at the beginning of the injection, and they propagate intermittently, with the mixture finally achieving a homogeneous distribution.

The spray structures of DMM (dimethoxy methane), DMC (dimethyl carbonate) and DME were investigated by Wu et al. [70] using laser-based visualization and PIV. Their analysis showed that the spray of oxygenated fuel shows an umbrella-shape structure, a larger spray angle and a shorter spray tip penetration, as compared to diesel fuel. Moreover, it also presents a weak large-scale heterogeneity and branch-like structure, finer droplets, a stronger interface and more violent vertical motion. Furthermore, their analysis also showed that the viscosity of oxygenated fuel has a significant effect on the atomization behavior.

An investigation of the characterization of the GDI flow field and stratification effects of fuel spray in a visualization engine using DPIV (digital particle image velocimetry) and entropy analysis were conducted by Lee and Lee [71]. Their analysis revealed a relationship between vorticity and entropy, which plays an important role in the diffusion process. The homogeneous diffusion rate of the spray was quantified using entropy analysis, and with this method, it was found that a homogeneous mixture distribution is more effective than the spray concentration in dissipating the momentum of the surrounding air in order to alter the injection timing. Moreover, an increase in the injection timing increases the homogeneous diffusion rate.

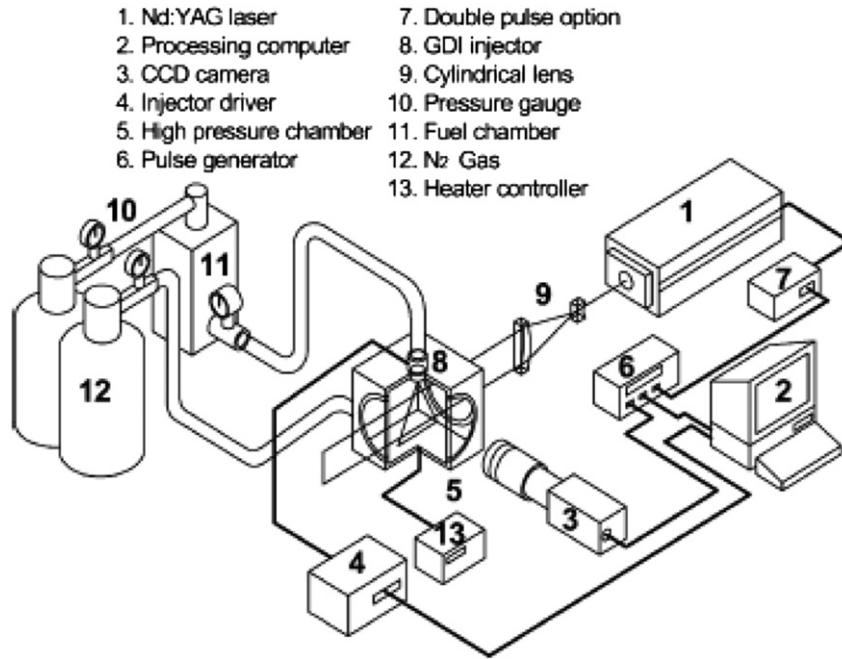


Fig. 10. Schematic diagram of experimental arrangement for PIV used by Lee et al. [67].

Myong et al. [72] studied the spray inner structure of an evaporating multi-component fuel using the PIV method in a CV vessel, as shown in Fig. 12. The tested single-component fuels were i-octane, n-dodecane and n-hexadecane. The multi-component fuels were designated as A, B and C, as shown in Table 1. Their analysis revealed that, in a HI-BP (high boiling fuel), the inner structure was very heterogeneous and a high concentration of the liquid phase in the spray tip occurred near the combustion chamber wall before evaporation, thus increasing the possibility of emissions of unburned HC (hydrocarbon). Moreover, it was found that evaporation was promoted by the addition of a LO-BP (low boiling point fuel), because it will lower the boiling point of the fuel.

2.3. Laser induced fluorescence (LIF) technique

LIF uses light emission from an atom or molecule following excitation by a laser beam. The principle mechanism in LIF is the excitation of a molecule from its initial lower electronic state to an

upper electronic state due to laser source. The processes in producing the LIF begin with excitation of a molecule by laser source, followed by the molecule returning to its initial state by stimulate emission. Then the molecule excites to higher state due to absorption of additional photon. Next, the internal energy produces rotational and vibration energy transfer due to collisions between the molecules. Later, the interactions between the individual atoms of the molecule produce internal energy transfer and dissociation. Finally, the originally and nearby populated state return to lower states through the emission of light and at the same time producing the LIF. The fluorescence signal can be expressed using equation (10);

$$P_{flu} = \eta_c Q V_c f_l(T) x_m N I_{v0} \frac{A_{21}}{A_{21} + Q_{21}} \frac{B_{12}}{1 + \frac{I_0}{I_{sat}}} \quad (10)$$

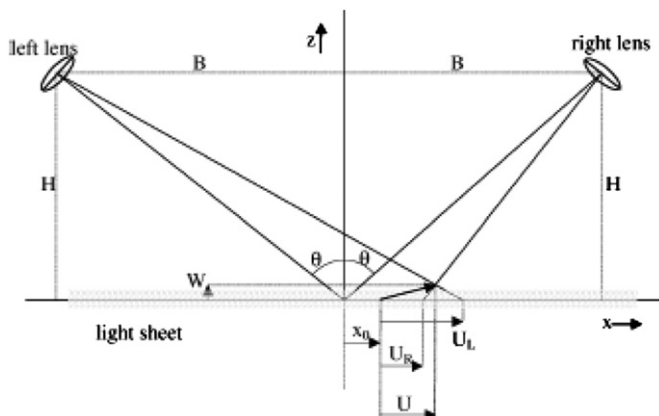


Fig. 11. Scheme of PIV stereoscopic configuration according to the angular displacement method (ADM) used by Stella et al. [69].

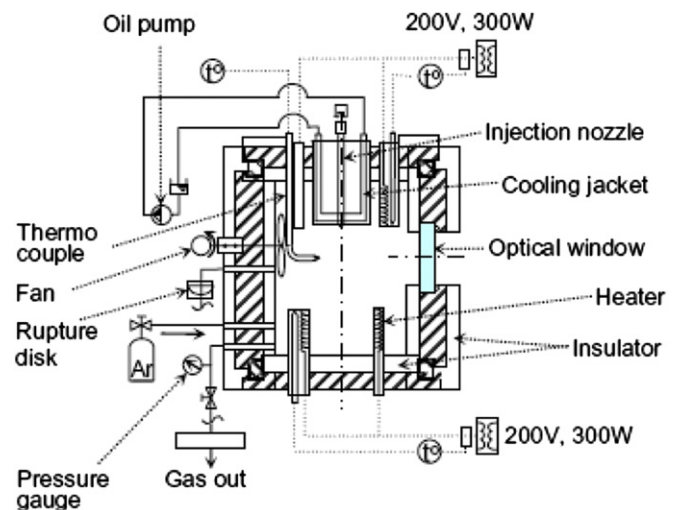


Fig. 12. Schematic cross-section of the constant-volume vessel used by Myong et al. [72].

Table 1
Experimental condition and fuel composition.

Injection nozzle	Type hole nozzle DLL-p	
	Diameter of hole (dn, mm)	02
	Length of hole (Ln, mm)	0.8
Test fuel	Single-component fuel (C ₈ H ₁₈ , C ₁₂ H ₂₆ , C ₁₆ H ₃₄) Multi-component fuel (Fuel A, Fuel B, Fuel C)	
Ambient temperature (T _{amb} , K)		500, 600, 700
Fuel temperature (T _{fuel} , K)		300, 362
Ambient density (ρ _{amb} , kg/m ³)		5, 15
Injection pressure (P _{inj} , MPa)		72
Ambient gas		Ar
Injection quantity (Q, mg)		12
Fuel component	Mass fraction of MCFs	
i-Octane:n-dodecane:n-hexadecane (C ₈ H ₁₈ :C ₁₂ H ₂₆ :C ₁₆ H ₃₄)	Fuel A = 6:3:1 Fuel B = 1:1:1 Fuel C = 1:3:6	
Injection duration (t _{inj} , ms)	Fuel A = 1.82 Fuel B = 1.82 Fuel C = 1.81	

LIF can be used to visualize the liquid droplet and fuel vapor at the same time. In fuel spray, although the liquid and vapor may be present at the same time, the signal from the liquid phase normally is much stronger than the signal from fuel vapor. The image can be obtained using an intensified CCD camera. To obtain the fluorescence image and to avoid elastically scattered light, an objective lens that is opaque to UV (ultra violet)-rays can be used with a color filter attached to the front of the lens. More information on LIF technique can be found in a review by Zhao and Ladommatos [38] and Desantes et al. [73] also had studied the limitations of the PLIEF (planar laser induced exciplex fluorescence) in diesel spray. The typical experimental setup for PLIEF technique is shown in Fig. 13.

2.3.1. Fuel phase, droplet sizing and species concentration in fuel spray

2.3.1.1. Fuel phases in spray. The spray structure and distribution characteristics of liquid and vapor phases in non-evaporating and

evaporating GDI fuel sprays were studied by Choi et al. [74] using LIEF (laser induced exciplex fluorescence) technique. The dopants used were 2% fluorobenzene and 9% DEMA (diethyl-methyl-amine) in 89% solution of hexane by volume. Meanwhile, PDA (phase doppler anemometry) technique was used to study the internal structure of the spray. The analysis showed there were two regions in the spray that was exposed by fluorescence intensity of liquid phase they were cone and mixing regions. In the mixing region, vortex flow of the vapor phase was observed.

2.3.1.2. Droplet sizing. Droplet combustion of methane in strained counter-flow diffusion flames was studied by Mercier et al. [75] using planar LIF. A mixture of CH₄ diluted with N₂ was injected from the lower nozzle and air from upper nozzle as shown in Fig. 14, and a monodisperse droplet generator was used to inject acetone droplet through the flame. PLIF will measure the OH radical and acetone was used to measure the spatial distribution of the fuel vapor and the structure of the flame front. The analysis showed that the droplet crossing strongly distorted the flame front. Further investigation revealed that, high velocity droplet led to local extinction of the flame front, and low velocity droplet could ignite within the flame front and burn on the oxidizer side.

An LIF image processing technique for measuring drop sizes in a pre-swirl spray was developed by Lee and Nishida [76]. A microscopic imaging technique was applied to obtain high spatial resolution LIF tomograms of the pre-swirl spray. 1 mm thick Nd:YAG laser sheet was used as a light source and the image was captured by high resolution CCD camera. Image processing was used to obtain the droplet size. The laser sheet-straddling large-sized droplets representing low intensity were screened effectively by applying the mean intensity ratio, and the small-sized droplets are relieved reasonably through the inspection of the line profile. They had concluded, the depth of field effects in droplet sizing by laser sheet imaging were effectively measured, but there were uncertainty with the Gaussian energy distribution of the laser sheet and the non-uniform distribution of the concentration of the fluorescent dye inside the droplets.

2.3.1.3. NO concentration in IC engine. The in-cylinder NO (nitrogen oxide) concentrations were studied by Verbeizen et al. [77] at various injection timing in a heavy duty diesel engine. The presence of the diffusion flame is related to the onset of NO formation within the laser probe volume observed using images from high-speed combustion. From the schlieren images, it was found that the initial combustion is too fuel-rich for thermal NO formation. Further study using numerical and experimental methods prove that the thermal mechanism is the major pathway for NO formation.

2.4. Phase Doppler particle anemometer (PDPA) technique

PDPA technique can be used for droplet sizing investigation in the fuel spray. The experimental measurement arrangement for PDPA is shown in Fig. 15. The PDPA system consists of an Ar-ion laser, a transmitter, a receiver and a data acquisition system. To obtain time-resolved data, the signal analyzer is synchronized with the injector driver using a digital delay generator. By averaging the captured droplets at all of the measurement points, the SMD (sauter mean diameter) at a specific time is obtained.

The atomization characteristic such as droplet velocity distribution is measured using PDPA technique. In this system, the Ar-ion laser is used as the light source and the signal analyzer is synchronized with the fuel injection signal to obtain the transient characteristics of the fuel atomization. The laser output and PMT (photomultiplier tube) voltage are set based on the data acquisition rate and signal intensity. When fuel droplets pass through the

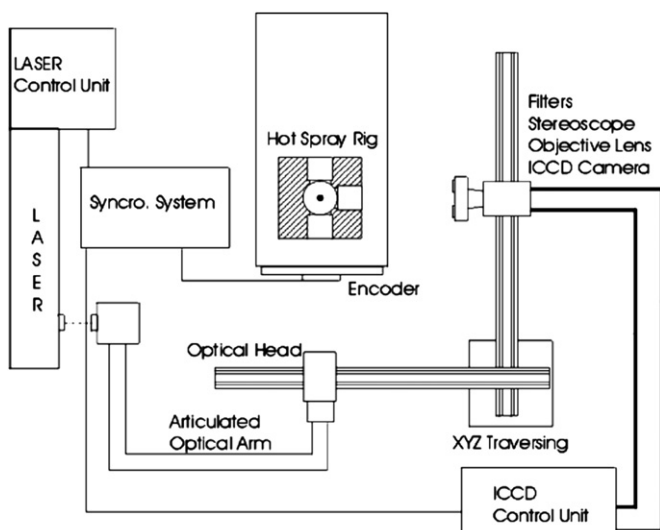


Fig. 13. Experimental layout for PLIEF technique by Desantes et al. [73].

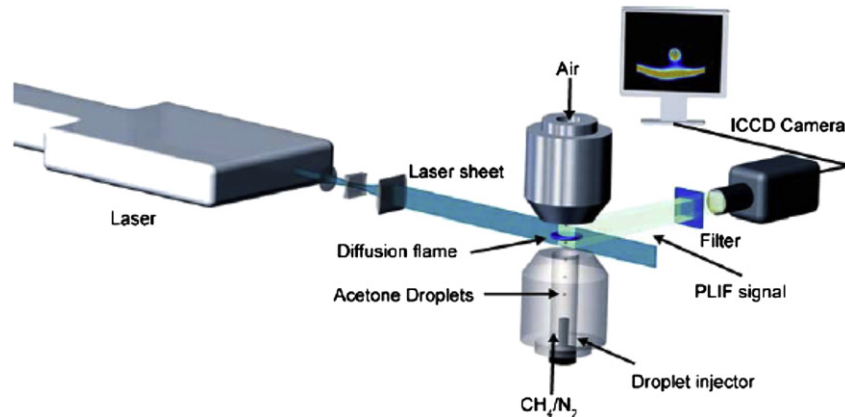


Fig. 14. Droplet combustion of methane in strained counter-flow diffusion flames measurement used by Mercier et al. [75].

measurement volume of fringe created by the laser beam from the Ar-ion laser, the dispersed beam is detected at the receiver. The detected phase difference and Doppler signal frequency are then converted to the mean droplet size and velocity. The fuel droplet size is obtained from the PDPA system for the analysis of the fuel atomization. The cutoff range of the droplet diameter measurement by using the droplet measuring system is set about 2–100 μm , and more than 20,000 spray droplets are collected and averaged for each measuring point. The representative SMD at a specific time is determined by averaging the captured droplets over all of the spray measurement area.

In order to utilize this technique, interference fringe pattern is needed to be created within a small volume in the spray. A scattered light signal is generated when a droplet moves through the small volume. The velocity of the droplet will be related to the temporal modulation, while the droplet size will be related to the spatial frequency. However, Zhao and Ladommatos [38] had stated that PDPA is not suitable for high density sprays; due to it only needs one droplet in the probe volume during the measurement. Moreover, this technique also cannot provide size distribution in a single transient injection. However, important information such as fuel droplet size and velocity, density, volume flux and time resolved can be obtained using this technique.

2.4.1. Fuel atomization measurement using PDPA

2.4.1.1. Structure of spray and fuel flow. Rantanen et al. [35] had studied the measurement of a diesel spray of a normal size nozzle and a large scale model using laser Doppler anemometry technique. The aim of this work is to study the effect of scaled experiments to the spray formation and atomization process. From the analysis of two test rigs (normal and scale 4:1) it was found that, the spray angle was 15% higher in the normal scale and the droplet size was scaled up to 80%. They had proved, scaling might caused inaccuracy in diesel sprays, but it can still provide valuable information about the break up and atomization mechanisms.

Chan and Turner [78] had measured the velocity inside a motored ICE using three-component laser Doppler anemometry as shown in Fig. 16. The aim of their study was to investigate the structure of the flow inside the combustion chamber of a motored ICE. A single cylinder 4-stroke research engine driven by an electric motor that was built for high-speed photographic studies was used. For three-component LDA optical system, a six-beam LDA system was assembled by combining a single-component Dantec 55X conventional modular optical system with a two-component four beam Dantec 60X Fibre-flow optical system. All the six beams were directed into the cylinder volume through the semi-circular window incorporated within the cylinder head of the model engine. The

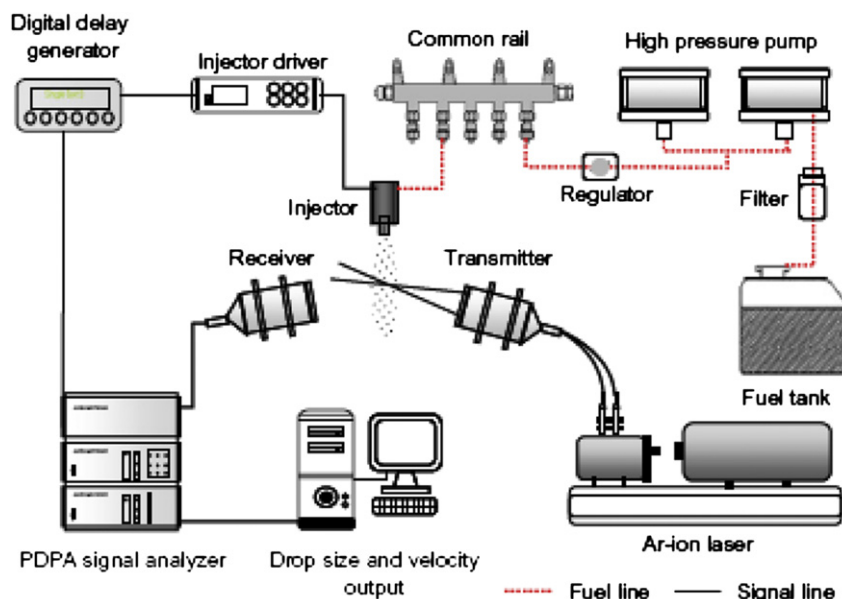


Fig. 15. Droplet particle analyzer system using PDPA used by Suh et al. [19].

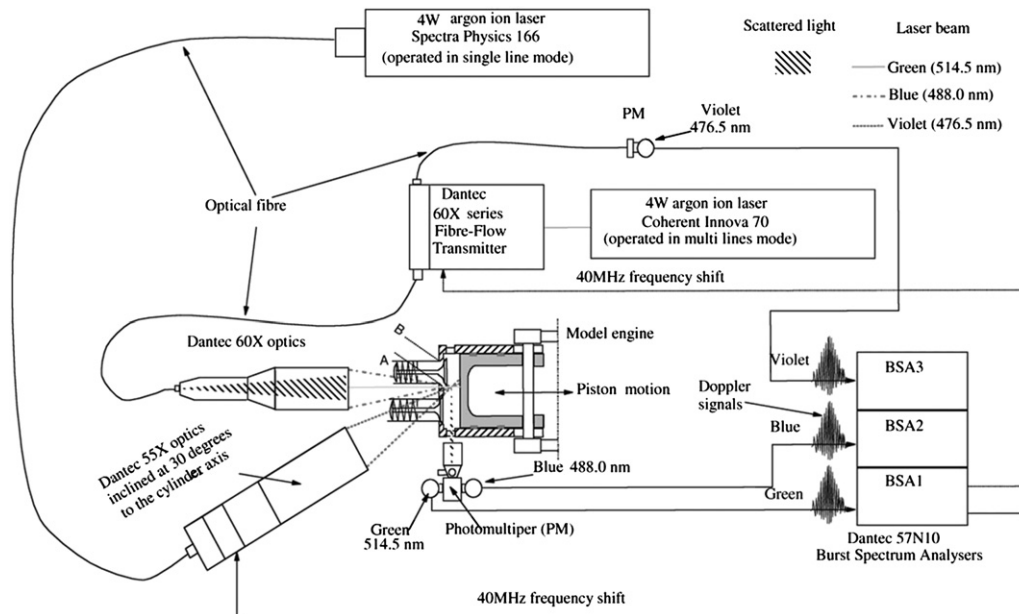


Fig. 16. Schematic of three-component LDA system used by Chan and Turner [78].

experiment of inclined inlet port configuration has revealed that the inclined port creates flow conditions more favorable to mixing process in the cylinder, because it generates a region with a relatively high shear and strong recirculation zones in the cylinder. Moreover it produces more nearly homogeneous flow structure at TDC (top dead center) during the compression stroke.

Doudou [79] experimentally studied the flow characteristics of the diesel spray in a pressurized vessel using PDPA. The axial velocity of the droplets was studied in the main parts of the spray: the leading edge, the central part and the trailing edge. From their analysis, it was found that the temporal distributions of the mean axial velocity and its rms were constant in the central spray region, but at the leading edge, they showed a maximum. The radial distribution of the normalized axial mean velocity was similar to that of the free gas jet; however, a higher normalized axial mean velocity value was displayed at the leading edge near the centerline axis. Moreover, a higher turbulence intensity of the axial velocity was observed in the leading edge region.

The effect of injection rate shape on the spray characteristics was also investigated by Benajes et al. [80]. Spray evolution was produced in three different injection rate shapes: *square*, *ramp* and *boot*, as shown in Fig. 17. It was found that the *square* injection rate always leads to higher spray tip penetration due to the higher pressure at the SOI, followed by the *ramp* and *boot* injection rates. A study of the cone angle also revealed that there is no influence of injection rate shape or injection pressure on the spray cone angle. By varying the injection pressure and duration for the same injected quantity, a small difference appears in the spray penetration, in which higher pressures lead to faster penetration. The combination of a higher injection pressure with a shorter duration produced a higher aperture angle at the beginning of the injection process.

Suh et al. [81] studied the spray and combustion characteristics of a biodiesel/diesel blended fuel in a DI common-rail diesel engine using visualization and PDPA techniques. The biodiesel fuel that was used in this work was derived from soybean oil with the blending ratios of 5% and 20% with diesel fuel. Experiments at various injection parameters were done in order to study the influence of the fuel blending ratio and pilot injection of biodiesel fuel on the spray characteristics, fuel injection rate, spray tip penetration and droplet size distribution. The spray characteristics

were studied using CV chamber and the spray visualization was captured using an ICCD camera. The atomization characteristic such as droplet velocity distribution was measured using PDPA technique. While for combustion characteristics measuring system, a common-rail diesel engine with four cylinders was installed on an eddy current dynamometer. It was found that a higher injection pressure was needed for the biodiesel blended fuel to achieve the same injection rate at a higher blending ratio. Their study also revealed that the spray tip penetration of biodiesel was similar to that of diesel, and the atomization characterization of biodiesel had a higher Sauter mean diameter and a lower spray velocity. Combustion analysis also revealed that the peak combustion pressure of the diesel and biodiesel blended fuel increased with increasing injection timing. Moreover, the combustion pressure of the biodiesel blended fuel was higher, as compared to diesel fuel.

Lin and Lin [82] had studied the spray characteristics of methyl esters from waste cooking oil at elevated temperatures. The methyl ester was treated with two-stage transesterification to lower its viscosity and to utilize emulsion to reduce the NO_x pollution. In this work, methanol was used to enhance the stability and viscosity of the emulsified fuel. The emulsification also had improved the methyl ester spray characteristics and decreased the NO_x emissions, at a temperature above 300 °C. The suggested optimal ratio was waste cooking oil methyl ester 74.5%, methanol 5%, water 20% and composite surfactant Span-Tween 0.5%.

2.4.1.2. Atomization characteristics. The effect of the injection driver on the macroscopic and microscopic atomization characteristics of a diesel fuel spray was also investigated by Suh et al. [19] using a piezo-driven injection system as shown in Fig. 18. The piezo-driven injection system has a few advantages such as a shorter injection delay and a fast opening time of the nozzle. It was found that a shorter injection delay and a faster opening time were produced by the piezo-driven injection system in comparison to the solenoid-driven injection system. There was only a small difference in the tip penetration, but the cone angle of the piezo-driven system was larger than that of the solenoid-driven injector. Moreover, the analysis also revealed that the atomization of the piezo-driven system was better, due to a faster response time and a higher injection rate.

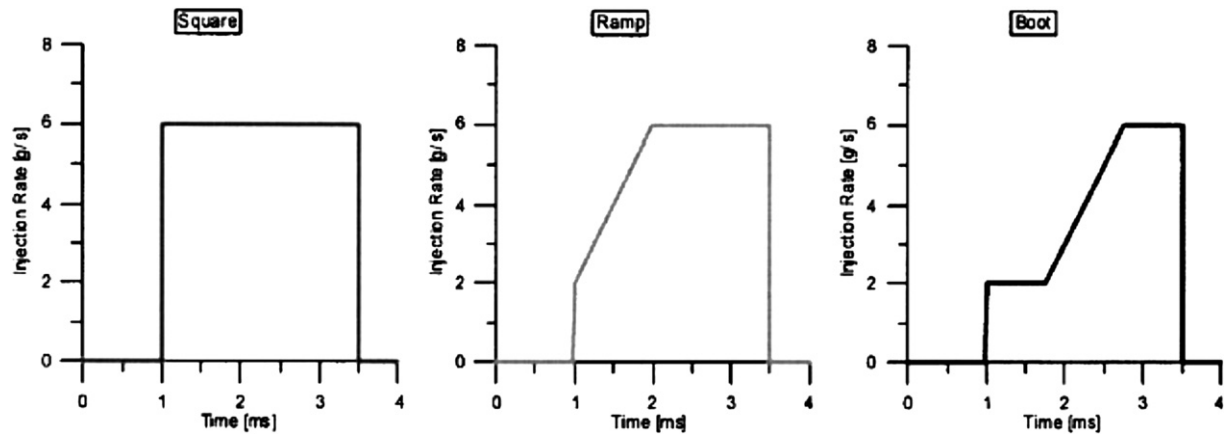


Fig. 17. “Square”, “Ramp” and “Boot” type ideal injection rates studied by Benajes et al. [80].

DME spray characteristics were studied by Suh and Lee [22] using a common-rail injection system in a diesel engine. This study focused on the atomization characteristics of DME and compared experimental and predicted results under various fuel injection conditions. There are two type of nozzle system that are used in this work; they are, a single-hole nozzle with 0.3 mm internal hole diameter (D) and 0.8 mm hole length (L) for spray visualization and droplet measuring experiments and for fuel injection rate measurement, different type of nozzle was installed to improve pressure detection at a low energizing duration. In order to study the injection rate characteristics of diesel and DME fuel, the injection rate measuring system was applied at various injection conditions. This measuring system is based on the pressure variation within a tube filled with the fuel. The pressure in the tube was kept constant at 3 MPa during fuel injection for the prevention of DME vapor generation in the tube. Pressure sensor and relief valve were installed to measure and to keep the constant line pressure higher than the vapor pressure of DME. In the injection

rate investigation, one thousand continuous injections were averaged for each test case. It was found that the experimental results of the spray tip penetration showed good agreement with the calculation results based on empirical equations, except during the earliest stage of the injection. Atomization analysis revealed that the DME showed better spray characteristics, as compared to conventional diesel fuel. Moreover, a shorter fuel injection delay and a lower maximum rate were produced by DME fuel.

The spray behavior and atomization characteristics of biodiesel and DME once again were studied by Kim et al. [83] under increased ambient pressure. They had found that the spray tip penetration and spray area decreased as the ambient pressure increased. The atomization performance of the biodiesel was found to be inferior compared to DME atomization performance.

SME (Soybean oil methyl ester) fuel injection and atomization characteristics were studied by Park et al. [84] using visualization and a droplet analyzer system. In this work, they used a single-hole nozzle 0.3 mm in diameter and 0.8 mm in orifice length that was controlled by a solenoid injector. The injection rates of the diesel and biodiesel fuels were measured and analyzed using an injection rate measuring system based on the Bosch method. From their analysis, it was found that, when the injection pressure increases, the peak injection rate will increase and advance due to the increase in the initial injection momentum. The injection rate of SME is also higher than that of diesel, due to its higher density. Moreover, the high ambient pressure induced in the combustion chamber also results in a shorter tip penetration of SME.

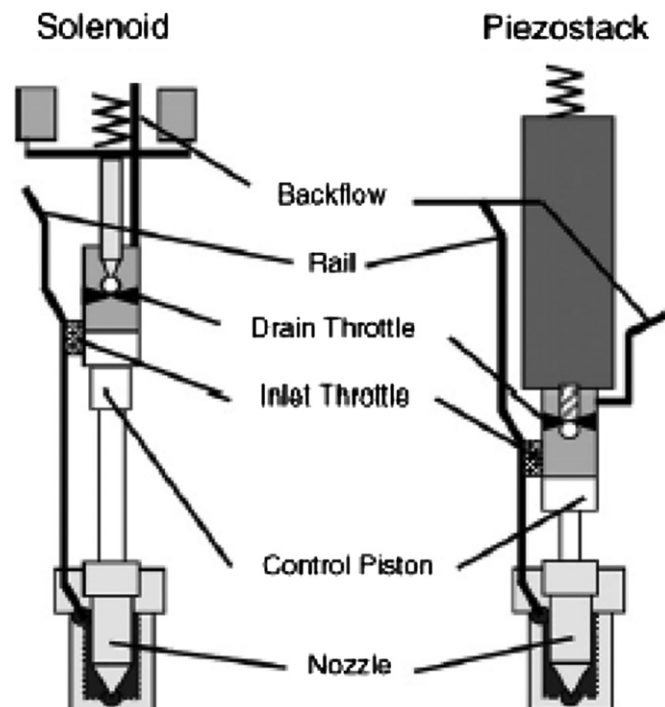


Fig. 18. Comparison of injector driver by Suh et al. [19].

Table 2
Comparison between PIV, LIF, PDPA and Visualization techniques.

Technique	Application and parameters obtained	Disadvantages and limitations
Visualization	Spray and combustion visualization. Macroscopic parameter such as spray geometry, penetration depth, wall impingement, and subsequent combustion.	Macroscopic spray parameters only.
PIV	Fuel sprays flow. Instantaneous whole field velocities.	Difficult to implement on dense sprays
LIF	Fuel concentration. Liquid and vapor fuel.	Quenching at high pressures and difficult to calibrate.
PDPA	Fuel sprays droplet size measurement. Fuel droplet size and velocity, density, volume flux and time resolved.	Not suitable for high density sprays.

Table 3

Summaries of studies of spray and combustion characteristics using optical techniques.

Type of fuel	Application	Analysis/Comment	Reference
Diesel	Spray formation, combustion and soot formation	- Fuel vapor extending beyond liquid core - Ignition close to the spray tip - Soot formed in the vapor core region	Bougie et al. [39]
Diesel	Evaporating characteristic and flame distribution	- Extinctions of two wavelengths of ultraviolet and visible light technique	Yoshizaki et al. [40]
Diesel	Macroscopic spray characteristics	- Present the way to determine the local spray angle, cone angle and penetration	Klein-Douwel et al. [41]
Diesel	Flames structure of wall-impinging diesel spray	- Higher OH chemiluminescence were observed for group-hole nozzles	Gao et al. [42]
Diesel	Initial stage of spray development	- Tip penetration shows linear dependencies at initial stages - Tip velocity proportional to $t^{1/2}$	Kostas et al. [43]
Gasoline	Mixture formation process from two hole nozzle DISI engine	- Droplet coalescence and penetration increased but decreased in vapor mass when HAA decreased - Vaporization and tip penetration rate increased with increased in injection pressure	Nishida et al. [44]
Natural gas and hydrogen	Spontaneous ignition and combustion	- Natural gas ignition need higher temperature - Shorter ignition delay for hydrogen	Ishiyama et al. [45]
DME	Fuel spray, flame structure, ignition	- Shorter ignition delay for DME - At 1.1 MPa, DME could be ignited at >770 K	Wakai et al. [46]
DME –Methyl ester blends	Injection and spray characteristics	- Shorter injection delay and injection duration, but higher peak injection duration for lower blending ratio - DME evaporated more faster	Bang and Lee [47]
Ethanol-Gasoline blends	Spray properties	- Similar spray pattern for both blended fuel and gasoline - Better evaporation when the fraction of ethanol increased at low pressure - No different in spray penetration at elevated pressure	Gao et al. [48]
Biodiesel blends	Spray and combustion development, effect of injection strategies	- HHR of biodiesel dominated by premixed combustion - Stronger fuel impingement, longer tip penetration with increasing biodiesel	Fang et al. [49]
Diesel/Biodiesel	Combustion process and NO _x emissions	- NO _x emissions for biodiesel increased under conventional combustion, but can be reduced under a certain strategy	Fang et al. [50]
Biodiesel blends (RME)	Macroscopic injection parameters	- Longer penetration, narrower cone angle, smaller spray volume due to high viscosity of RME	Desantes et al. [51]
Biodiesel blends (RME)	liquid-phase fuel penetration, soot luminosity and time-resolved intensified imaging	- Fuel penetration increases linearly with blending rates - Decrease of ignition delay for an increase of RME blend rate	Pastor et al. [52]
Gasoline/multi-component fuel	Fuel deposition burning in PFI spark-ignition engine	- Diffusion-controlled near valves due to fuel film deposition - soot amount near the valves decreased for advancing ignition - higher level of soot were observed when the intake valve open	Merola SS and Vaglieco BM [53]
Gasoline	Fuel injection strategy	- specific fuel consumption and emissions improved for the proposed injection strategies - higher combustion efficiency for double injection	Merola SS et al. [54]
Diesel	Effect of cavitation on the internal flow	- Cavitation leads to an increment in cone angle - Whole outlet velocity increases when cavitation is initiated	Payri et al. [55]
Water	Structure and evolution of cavitation and its effects on jet pattern	- Proposed conceptual model to explain the development of asymmetric spray atomization	Ganippa et al. [56]
Diesel/biodiesel	Criteria for cavitation inception and its flow characteristics	- There are 4 regimes in nozzle cavitation flow, that are; turbulent flow, beginning of cavitation, cavitation growth and hydraulic flip - Cavitation decreased with an increase in the Reynolds number and Weber number	Suh et al. [57]
Diesel	Impact of injection pressure	- Impact of high injection pressure of biodiesel	Delacourt et al. [58]
Diesel/Biodiesel	Spray characteristics under ultra-high injections	- Longer injection delay and spray tip penetration, but smaller spray angle, area and volume for biodiesel - Larger SMD for biodiesel	Wang et al. [59]
Diesel	Effect of orifice diameter	- Lift-off length decreases with decreasing orifice diameter - Total soot incandescence decreases as the orifice diameter decreases - Normalized flame length decreases as the orifice diameter increases	Pickett and siebers [60]
Diesel	Effect of nozzle geometry	- Velocity and mass flow rate strongly influenced by cavitation	Payri et al. [61]
Diesel	Effect of nozzle geometry to combustion characteristics	- CH-radicals was influenced by spray behavior - OH-radicals can be considered as measurement of ignition - Observed the influence of chamber conditions and injection pressure	Payri et al. [62]
Diesel	Impact of injection angle	- Different HRR were observed - Wall impingement detected on the 70° tip, and produced 2 types of flame - 150° tip produced weak flame	Fang et al. [63]
Gasoline	Swirling injector	- Greater air pressure drop at higher injection pressure - Higher air pressure at nozzle exit at higher fuel temperatures	Moon et al. [64]

(continued on next page)

Table 3 (continued)

Type of fuel	Application	Analysis/Comment	Reference
Natural gas-hydrogen blends	Cyclic variation	- Cyclic variations initiated at early stage of flame development	Wang et al. [65]
n-heptane	NO _x control	- Addition of hydrogen caused a flame kernel - Enhanced fuel/air mixing reduced NO _x - NO _x reduced with increasing injection pressure	Kitamura et al. [66]
Propane	Turbulent premixed flame	- Use of 3-component PIV, very effective for turbulent combustion process investigation	Stella et al. [67]
Gasoline	Spray behavior, Fuel distribution	- Fuel spray propagates widely in the downstream direction - Entropies are higher when the ambient temperature is higher than fuel evaporation temperature	Lee et al. [67]
DMM, DMC and DME	Spray structure, atomization	- Larger spray angle, shorter tip penetration for oxygenated fuel - Viscosity of oxygenated fuel has significant effect on the atomization	Wu et al. [70]
Gasoline	GDI flow field, Stratification effects	- Revealed relationship between vorticity and entropy - Increase in injection timings increases the homogeneous diffusion rate	Lee and Lee [71]
i-octane, n-dodecane and n-hexadecane, and the multi-component fuels	Spray inner structure, fuel concentration, fuel evaporation	- Inner structure is very heterogeneous and high concentration of liquid phase for HI-BP - Evaporation is promoted by addition LO-BP	Myong et al. [72]
Gasoline	Spray structure, liquid and vapor phases	- Two regions in the spray, they are; cone and mixing regions - In the mixing region, vortex flow of the vapor phase was observed	Choi et al. [74]
Methane	Droplet combustion of methane in strained counter-flow diffusion flames	- Droplet crossing strongly distorted the flame front - High velocity droplet led to local extinction of the flame front, and low velocity droplet could ignite within the flame front and burn on the oxidizer side	Mercier et al. [75]
Gasoline	LIF image processing technique for measuring drop sizes in a pre-swirl spray	- The depth of field effects in droplet sizing by laser sheet imaging were effectively measured	Lee and Nishida [76]
Diesel	NO concentration in diesel engine	- Initial combustion is too fuel-rich for thermal NO formation - Thermal mechanism is the major pathway for NO formation	Verbeizen et al. [77]
Diesel	Measurement of a diesel spray of a normal size nozzle and a large scale model	- Scaling caused inaccuracy in diesel spray but provided valuable information about breakup and atomization	Rantanen et al. [35]
–	Flow structure	- Inclined port creates flow conditions more favorable to mixing process - Produces more nearly homogeneous flow structure at TDC	Chan and Turner [78]
Diesel	Spray flow characteristics	- Temporal distributions were constant in the central spray region - Higher turbulence intensity of the axial velocity in the leading edge region	Doudou [79]
Diesel	Effect of injection rate shape	- Square injection rate leads to higher tip penetration - No influence of injection rate to cone angle - Higher aperture angle obtained by combined a higher injection pressure with shorter duration	Benajes et al. [80]
Biodiesel and diesel blended	Spray and combustion, atomization, SMD, spray velocity	- Higher injection pressure is needed for biodiesel blended fuel - Similar tip penetration and higher SMD were observed for biodiesel	Suh et al. [81]
Methyl ester	Spray characteristics of methyl ester from WCO at elevated temperature	- Viscosity of methyl ester was reduced by two-stage transesterification - Emulsification improved the spray characteristics and decreased the NO _x	Lin and Lin [82]
Diesel	Effect of injection driver	- Shorter injection delay, faster opening time, larger cone angle and better atomization for piezo-driven injection system	Suh et al. [19]
DME	Fuel atomization	- DME showed better spray characteristics, shorter injection delay and lower maximum rate	Suh and Lee [22]
DME	Spray behavior and atomization characteristics	- Decrease spray tip penetration and cone angle as the ambient pressure increases - Peak injection rate increase and advance when the injection pressure increases	Kim et al. [83]
Soybean oil methyl ester	Spray structure and atomization	- Higher injection rate of SME compared to diesel - Reduction in mean droplet velocity for peak valve lifts of less than 3 mm.	Park et al. [84]
Gasoline	Effect of variable valve lift	- Reduction in mean droplet velocity for peak valve lifts of less than 3 mm.	Begg et al. [85]
Liquefied butane	Droplet velocity and diameter	- Narrowed cone angle during quasi-steady spray period - Spray evaporates faster at 0.37 MPa	Koo et al. [86]
Diesel	Spray droplet velocity of convergent nozzles	- Higher axial velocity was displayed for nozzles with higher spray momentum	Payri et al. [87]

The airflow and fuel spray interaction in a variable valve lift in a PFI engine were studied by Begg et al. [85] using a PDA technique. The experiment was done in a steady state flow rig fitted with a modified cylinder head, and the intake valve lift was varied manually. It was found that the mean droplet diameter was reduced up to 50% for peak valve lifts of less than 3 mm.

2.4.1.3. Droplet velocity characterization. The droplet velocity and diameter of liquefied butane spray from pintle-type injector were studied by Koo et al. [86]. Two component phase/Doppler particle analyzer and traverser were used to obtain the velocity and diameter of the fuel droplet. The analysis showed that a narrowed cone angle was observed during the quasi-steady spray period at 0.37 MPa chamber pressure compared to 0.15 MPa. The spray also

evaporated faster at 0.37 MPa, and the SMDs were similar at spray edges but nearly doubled in the interior.

Spray droplet velocity characterization for convergent nozzles was studied by Payri et al. [87] in order to obtain the local speed of fuel droplets at various points of diesel DI sprays using PDPA techniques. Various orifice diameters of convergent nozzles were investigated, and the experimental measurements were compared to theoretical results. Their analysis showed that the experimental results exhibited a high level of agreement with a Gaussian profile. The experimental data also showed that the velocity in the spray axis depends inversely on the axial position. Moreover, a higher axial velocity was displayed for nozzles with higher spray momentum.

2.5. Summary and recommendations

There are various methods that can be used to capture the spray and combustion images within the combustion chamber. Different methods will provide different information. Using visualization methods, macroscopic parameters can be determined, and using the PIV, LIF and PDPA techniques, information can be found regarding the microscopic parameters. However, for combustion characteristics studies, visualization technique is very useful in gathering the information from the combustion chamber. Additionally, three-component PIV and PDPA techniques can be used to provide better information on the spray phenomena in IC engines. The comparison for each technique is shown in Table 2 and the summary of studies on spray using optical method is shown in Table 3.

The type of alternative fuels that were studied can be classified into three categories, they are; oxygenated fuel, gaseous fuel and biodiesel/diesel blended fuel. Most of the oxygenated fuels are tested with a diesel engine operating system. The oxygenated fuels were studied from various aspects; the spray structure and motion, the fuel concentration, the fuel evaporation and its atomization and were compared to diesel fuel spray and combustion. From their studies, the comparison between some of oxygenated fuels and diesel fuel shows; shorter ignition delay and lower temperature for ignition, shorter spray tip penetration, better spray characteristics and higher injection rate are needed for higher viscosity oxygenated fuels compared to diesel fuel. Only few studies had focused on the NO_x emissions of the oxygenated fuel. While for gaseous fuel, they were focusing on the visualization of the ignition and combustion of hydrogen and natural gas. These two types of gaseous fuel are frequently studied due to their high calorific values that make them easily to combust and ease to use in IC engines. The spray and combustion of LPG (liquefied petroleum gas) and CNG (compressed natural gas) also need to be studied as they have been widely used in IC engines. In order to study the flow pattern and flow velocity of a gaseous fuel, seeding particles are essential to be added inside the combustion chamber due to fine molecules of the gaseous fuel, thus making PIV and LIF the most suitable methods for this kind of measurement. The biodiesel/diesel blended fuel studies were concentrated on both macroscopic and microscopic parameters such as their spray and combustion development, atomization, SMD and spray velocity. Although there were many reports on the combustion characteristics, but the fundamental data of the spray and combustion phenomena is still limited especially on the fuel concentration and evaporation. Further research can also be conducted on the effect of changing of nozzle sizes and the effect of injection pressures.

For SI engine combustion, further research can be done on the effect of the compression ratio, the combustion chamber surface/volume ratio & geometry, the overall equivalence ratio, the intake manifold temperature, the intake manifold pressure/throttle position, the wall temperature (or rate of engine cooling), the distance of spark plug from cylinder axis, the in-cylinder fluid motion (swirl,

tumble, squish), the exhaust gas recirculation (EGR) and the spark timing to the spray and combustion characterization. Previously, only few studies have been done on SI engine, for example the use of GDI fuel spray and effect of two-hole nozzle DISI engine, that leaves a wide scope for researchers in this area.

For CI engine, they were studies on DI engine, but none on IDI (indirect injection). The injection system in CI engine can be classified into three categories, they are; mechanical injection systems (in line, rotary/distributor type), unit injection system (mechanical, electronic or hydraulically controlled) and CRI (common-rail injection) systems. Previously, only the effect of piezo-driven injection was studied by Suh et al. [19].

The stricter emission regulation has also led the researcher to study the mixing and combustion process of alternative fuels. Although some of the measurements are done in the CV vessel, it is also essential to study their emission level that was not studied in previously. As the detail of spray and combustion data can be obtained, it will provide the way of controlling the combustion process, and minimizing the emission level. Any fuel injection system directly influences diesel combustion by changes in fuel injection pressure, injection timing, injected fuel quantity, rate of fuel injection, quality of spray “atomization”, possibility of multiple-injection events and after-injection, dribble & secondary injection. Previously, only the effect of changing injection parameters such as injection pressure, injection rate shape and effect of nozzles/orifice number, geometry and angle were studied, hence, leaving a broad area to be explored in this area of studies. Moreover, with an optical engine, it is possible to study and control the abnormal combustion phenomena such as engine knock.

3. Conclusion

A thorough review of published works on spray and combustion characterization of IC engines using optical measuring technique has been made. Previous works have been conducted in either modified engines or CV vessels, with both systems being equipped with an optical access made of quartz or fused silica. More investigations have to be carried out on the fundamental of spray and combustion of fuel in IC engines. Hence, there is a wide scope for researchers in this area to develop efficient and environmentally clean system. Alternative fuel, if properly engineered, can be an excellent candidate to replaced fossil based fuel, to be applied in automobiles, stirling engines as well as in domestic and industrial burners. There are still lots of alternative fuels that can be studied such as a low heating value producer gas. The fast development in optical measuring techniques is a promising breakthrough in understanding the mixing process, as this provides ways in controlling the combustion process. There are other optical measurement techniques that can be used such as optical patternator which is suitable for dense spray as suggested by Sankar [2]. The combustion process can be improved further by enhancing the mixing process, incorporating suitable combustion environment, and changing the parameters that critically influence the combustion in a practical perspective. Moreover, the emissions level studies are essential even though the experimental works were only done in CV vessels.

Acknowledgement

This research has been financially supported by the USM-RU-PPGRS provided by UNIVERSITI SAINS MALAYSIA.

References

- [1] Ramadhas AS, Jayaraj S, Muraleedharan C. Use of vegetable as IC engine fuels – A review. *Renew Energ* 2004;29:727–42.

- [2] Sankar SV, Maher KE, Robart DM, Bachalo WD. Rapid characterization of fuel atomizers using an optical patternator. *J Eng Gas Turb Power* 1999;121:409–14.
- [3] Su TF, Chang CT, Reitz RD. Effects of injection pressure and nozzle geometry on spray SMD and D.I. emissions. *SAE Paper* 952360; 1995.
- [4] Nehmer DA, Reitz RD. Measurement of the effect of injection rate and split injections on diesel engine Soot and NOx emissions. *SAE Paper* 940668; 1994.
- [5] Zhang L. A study of pilot injection in a DI diesel engine. *SAE Paper* 1999-01-3493; 1999.
- [6] Tanaka T, Ando A, Ishizaka K. Study on pilot injection of DI diesel engine using common-rail injection system. *JSAE* 2002;23:297–302.
- [7] Onishi S, Hong Jo S, Shoda K, Do Jo P, Kato S. Active thermo-atmosphere combustion (ATAC) — A new combustion process for internal combustion engines. *SAE Paper* 790501; 1979.
- [8] Shao J, Yan Y, Greeves G, Smith S. Quantitative characterization of diesel sprays using digital imaging techniques. *Meas Sci Technol* 2003;14:1110–6.
- [9] Pierpont DA, Reitz RD. The effects of injection pressure and nozzle geometry on D.I. diesel emissions and performance. *SAE Paper* 950604; 1995.
- [10] McCreath CG, Beér JM. A review of drop size measurement in fuel sprays. *Appl Energy* 1976;2(1):3–15.
- [11] Jones AR. A review of drop size measurement—the application of techniques to dense fuel sprays. *Prog Energy Combust* 1977;3(4):225–34.
- [12] Chigier NA. The atomization and burning of liquid fuel sprays. *Prog Energy Combust* 1976;2(2):97–114.
- [13] Seth B, Aggarwal SK, Sirignano WA. Flame propagation through an air-fuel spray mixture with transient droplet vaporization. *Combust Flame* 1980;39(2):149–68.
- [14] Banhawey YE, Whitelaw JH. Experimental study of the interaction between a fuel spray and surrounding combustion air. *Combust Flame* 1981;42:253–75.
- [15] Yule AJ, Seng CA, Felton PG, Ungut A, Chigier NA. A study of vaporizing fuel sprays by laser techniques. *Combust Flame* 1982;44(1–3):71–84.
- [16] Nakabe K, Mizutani Y, Hirao T, Fujioka H. An experimental study on detailed flame structure of liquid fuel sprays with and without gaseous fuel. *Combust Flame* 1991;1-2:3–14.
- [17] Presser C, Gupta AK, Avedisian CT, Semerjian HG. Fuel property effects on the structure of spray flames. *Sym Int Combust Proc* 1991;23(1):1361–7.
- [18] Senda J, Kobayashi M, Tanabe Y, Fujimoto H. Visualization and quantitative analysis of the fuel vapor concentration in diesel spray. *JSAE Review* 1994;15(2):149–56.
- [19] Suh HK, Park SW, Lee CS. Effect of piezo-driven injection system on the macroscopic and microscopic atomization characteristics of diesel fuel spray. *Fuel* 2007;86:2833–45.
- [20] Kawano D, Senda J, Kawakami K, Shimada A, Fujimoto H. Fuel design concept for low emission in engine system 3rd report: analysis of spray characteristics for mixed fuels. *SAE Paper* 2002-01-0220; 2002.
- [21] Kawanabe H, Kondo C, Kohori S, Shioji M. Simultaneous measurements of velocity and scalar fields in a turbulent jet using PIV and LIF. *JSME* 2008;74(742):1411–8.
- [22] Suh HK, Lee CS. Experimental and analytical study on the spray characteristics of dimethyl ether (DME) and diesel fuels within a common-rail injection system in a diesel engine. *Fuel* 2008;87:925–32.
- [23] Dent JC. Basis for the comparison of various experimental methods for studying spray penetration. *SAE Paper* 710571; 1971.
- [24] Hiroyasu H, Arai M. Structures of fuels sprays in Diesel engines. *SAE Paper* 1990;900475.
- [25] Bosch W. The fuel rate indicator: a new measuring instrument for display of the characteristics of individual injection. *SAE Paper*; 1966:660–749.
- [26] Heywood JB. Internal combustion engine fundamental. New York: McGraw-Hill International Editions; 1988.
- [27] Dan T, Senda J, Fujimoto H. Organized structure and motion in diesel spray. *SAE Paper* 970641; 1997.
- [28] Kosaka H, Kamimoto T. A study on the structure of transients sprays. *JSME* 1999;65(640):272–7.
- [29] Yuyama R, Chikahisa T, Kikuta K, Hishinuma Y. Entropy analysis of microscopic diffusion phenomena in diesel sprays. *COMODIA*; 2001:542–50.
- [30] Zainal ZA, Soid SN. Modeling of combustion characteristic in diesel engine fueled by producer gas. *SAE Paper* 2007-01-2130; 2007.
- [31] Ferguson CR, Kirkpatrick AT. Internal combustion engines. 2nd ed. New York: John Wiley & Sons Inc; 2001.
- [32] Palopski T. The use of dimensional analysis and model experiments in the research of fuel injection (in Finnish). Helsinki University of technology, Laboratory of energy engineering and environmental protection, Espoo.
- [33] Walzel P. Advantages and limits in large scale modeling of atomizers. *ICLASS*; 1982:187–94.
- [34] Soteriou C, Andrews R, Smith M. Direct injection diesel sprays and the effect of cavitation and hydraulic flip on atomization. *SAE Paper* 950080; 1995.
- [35] Rantanen P, Valkonen A, Cronhjort. Measurement of a diesel spray with a normal size nozzle and a large-scale model. *Int J Heat Fluid Fl* 1999;20:545–51.
- [36] Roisman IV, Araneo L, Tropea C. Effect of ambient pressure on penetration of a diesel spray. *Int J Multiphas Flow* 2007;33:904–20.
- [37] Chigier N. Optical imaging of sprays. *Prog Energy Combust* 1991;17(3):211–62.
- [38] Zhao H, Ladommatos N. Optical Diagnostics for in-cylinder mixture formation measurement in IC engines. *Prog Energy Combust* 1998;24:297–336.
- [39] Bougie B, Tulej M, Dreier T, Dam NJ, Ter Meulen JJ, Gerber T. Optical diagnostics of diesel spray injections and combustion in a high-pressure high-temperature cell. *Appl Phys B-Lasers O* 2005;80:1039–45.
- [40] Yoshizaki T, Yamamoto O, Nishida K, Hiroyasu H, Suzuki M. Evaporating spray and flame distributions in the combustion chamber of a direct injection diesel engine. *JSAE Rev* 1997;18(3):219–24.
- [41] Klein-Douwel RJH, Frijters PJM, Somers LMT, de Boer WA, Baert RSG. Macroscopic diesel fuel spray shadowgraphy using high speed digital imaging in a high pressure cell. *Fuel* 2007;86:1994–2007.
- [42] Gao J, Moon S, Zhang Y, Nishida K, Matsumoto Y. Flame structure of wall-impinging diesel fuel sprays injected by group-hole nozzle. *Combust Flame* 2009;156(6):1263–77.
- [43] Kostas J, Honnery D, Soria J. Time resolved measurements of the initial stages of fuel spray penetration. *Fuel* 2009;88(11):2225–37.
- [44] Nishida K, Tian J, Sumoto Y, Long W, Sato K, Yamakawa M. An experimental and numerical study on sprays injected from two-hole nozzles for DISI engines. *Fuel* 2009;88(9):1634–42.
- [45] Ishiyama T, Shioji M, Ihara T, Inoue T, Takada N. Characteristics of spontaneous ignition and combustion in unsteady high speed gaseous fuel jets. *SAE Paper* 2003-01-1922; 2003.
- [46] Wakai K, Nishida K, Yoshizaki T, Hiroyasu H. Spray and ignition characteristics of di-methyl ether injected by a DI diesel injector. *COMODIA*; 1998:537–42.
- [47] Bang SH, Lee CS. Fuel injection characteristics and spray behavior of DME blended with methyl ester derived from soybean oil. *Fuel* 2010;89:797–800.
- [48] Gao J, Jiang D, Huang Z. Spray properties of alternative fuels: a comparative analysis of ethanol-gasoline blends and gasoline. *Fuel* 2007;86:1646–50.
- [49] Fang T, Lin YC, Foong TM, Lee CF. Biodiesel combustion in an optical HSDI diesel engine under low load premixed combustion conditions. *Fuel* 2009;88(11):2154–62.
- [50] Fang T, Lee CF. Bio-diesel effects on combustion processes in an HSDI diesel engine using advanced injection strategies. *P Combust Inst* 2009;32(2):2785–92.
- [51] Desantes JM, Payri R, Garcia A, Manin J. Experimental study of biodiesel blends' effects on diesel injection processes. *Energy Fuel* 2009;23:3227–35.
- [52] Pastor JV, Payri R, Gimeno J, Nerva JG. Experimental study on RME blends: liquid-phase fuel penetration, chemiluminescence, and soot luminosity in diesel-like conditions. *Energy Fuel* 2009;23:5899–915.
- [53] Merola SS, Vaglieco BM. Optical investigations of fuel deposition burning in ported fuel injection (PFI) spark-ignition (SI) engine. *Energy* 2009;34(12):2108–15.
- [54] Merola SS, Sementa P, Tornatore C, Vaglieco BM. Effect of the fuel injection strategy on the combustion process in a PFI boosted spark-ignition engine. *Energy* 2010;35(2):1094–100.
- [55] Payri F, Bermudez V, Payri P, Salvador FJ. The influence of cavitation on the internal flow and the spray characteristics in diesel injection nozzles. *Fuel* 2004;83:419–31.
- [56] Ganippa LC, Bark G, Andersson S, Chomiak J. Cavitation: a contributory factor in the transition from symmetric to asymmetric jets in cross-flow nozzles. *Exp Fluids* 2004;36:627–34.
- [57] Suh HK, Park SH, Lee CS. Experimental investigation of nozzle cavitating flow characteristics for diesel and biodiesel fuels. *Int J Automot Technol* 2008;9:217–24.
- [58] Delacourt E, Desmet B, Besson B. Characterisation of very high pressure diesel sprays using digital imaging techniques. *Fuel* 2005;85:859–67.
- [59] Wang X, Huang Z, Kuti OA, Zhang W, Nishida K. Experimental and analytical study of biodiesel and diesel spray characteristics under ultra-high injection pressure. *Int J Heat Fluid Fl* 2010;31(4):656–66.
- [60] Pickett LM, Siebers DL. Orifice diameter effects on diesel fuel jet flame structure. *J Eng Gas Turb Power* 2005;127:187–96.
- [61] Payri R, Salvador FJ, Gimeno J, Zapata LD. Diesel nozzle geometry influence on spray liquid-phase fuel penetration in evaporative conditions. *Fuel* 2008;87:1165–76.
- [62] Payri R, Salvador FJ, Gimeno J, de la Morena J. Effects of nozzle geometry on direct injection diesel engine combustion process. *Appl Therm Eng* 2009;29:2051–60.
- [63] Fang T, Coverdill RE, Lee CF, White RA. Effects of injection angles on combustion processes using multiple injection strategies in an HSDI diesel engine. *Fuel* 2008;87:3232–9.
- [64] Moon S, Abo-Serie E, Bae C. Air flow and pressure inside a pressure-swirl spray and their effects on spray development. *Exp Thermal Fluid Sci* 2009;33:222–31.
- [65] Wang J, Huang Z, Miao H, Wang X, Jiang D. Study of cyclic variations of direct-injection combustion fueled with natural gas-hydrogen blends using a constant volume vessel. *Int J Hydrogen Energy* 2008;33:7580–91.
- [66] Kitamura Y, Kee SS, Mohammadi A, Ishiyama T, Shioji M. Study on NOx control in direct-injection PCCI combustion-fundamental investigation using a constant-volume vessel. *SAE Paper*; 2006. 2006-01-0919.
- [67] Lee KH, Lee CH, Lee CS. An experimental study on the spray behavior and fuel distribution of GDI injectors using the entropy analysis and PIV method. *Fuel* 2004;83:971–80.
- [68] Kompenhans J, Kähler C. Particle image velocimetry — An advanced experimental tool for the investigation of turbulent flow fields. *Eis Ser Therm Fluid* 2002;5:79–94.
- [69] Stella A, Guj G, Kompenhans J, Richard H, Raffel M. Three-component particle image velocimetry measurements in premixed flames. *Aerospace Sci Technol* 2001;5:357–64.
- [70] Wu Z, Zhu Z, Huang Z. An experimental study on the spray structure of oxygenated fuel using laser-based visualization and particle image velocimetry. *Fuel* 2006;85:1458–64.
- [71] Lee KH, Lee CH. Characterization of the flow field and stratification effects of fuel spray in a visualization engine using DPIV and entropy analysis. *Exp Therm Fluid Sci* 2007;31:579–92.

- [72] Myong KJ, Suzuki H, Senda J, Fujimoto H. Spray inner structure of evaporating multi-component fuel. *Fuel* 2008;87:202–10.
- [73] Desantes JM, Pastor JV, Pastor JM, Julia JE. Limitations on the use of the planar laser induced exciplex fluorescence technique in diesel sprays. *Fuel* 2005;84:2301–15.
- [74] Choi DS, Choi GM, Kim DJ. Spray structures and vaporizing characteristics of a GDI fuel spray. *KSME Int J* 2002;16:999–1008.
- [75] Mercier X, Orain M, Grisch F. Investigation of droplet combustion in strained counterflow diffusion flames using planar laser-induced fluorescence. *Appl Phys B-Lasers O* 2007;88:151–60.
- [76] Lee JK, Nishida K. Development of an LIF image processing technique for measuring drop sizes in a pre-swirl spray. *Int J Automot Technol* 2008;9:381–90.
- [77] Verbeizen K, Donkerbroek AJ, Klein-Douwlel RJH, Vliet APV, Frijters PJM, Seykens XLJ, et al. Diesel combustion: in-cylinder NO concentrations in relation to injection timing. *Combust Flame* 2007;151:333–46.
- [78] Chan VSS, Turner JT. Velocity measurement inside a motored internal combustion engine using three-component laser Doppler anemometry. *Opt Laser Technol* 2000;32:557–66.
- [79] Doudou A. Turbulent flow study of an isothermal diesel injected by a common rail system. *Fuel* 2005;84:287–98.
- [80] Benajes J, Payri R, Molina S, Soare V. Investigation of the influence of injection rate shaping on the spray characteristics in a diesel common-rail system equipped with a piston amplifier. *J Fluids Eng-T ASME* 2005;127:1102–10.
- [81] Suh HK, Roh HG, Lee CS. Spray and combustion characteristics of biodiesel/diesel blended fuel in a direct injection common-rail diesel engine. *J Eng Gas Turb Power* 2008;130:032807–9.
- [82] Lin YS, Lin HP. Study on the spray characteristics of methyl esters from waste cooking oil at elevated temperature. *Renew Energ* 2010;35:1900–7.
- [83] Kim JK, Park SH, Lee CS. A study on the macroscopic spray behavior and atomization characteristics of biodiesel and dimethyl ether sprays under increased ambient pressure. *Fuel Process Technol* 2010;91(3):354–63.
- [84] Park SH, Kim HJ, Suh HK, Lee CS. A study on the fuel injection and atomization characteristics of soybean oil methyl ester (SME). *Int J Heat Fluid* 2009;30:108–16.
- [85] Begg SM, Hindle MP, Cowell T, Heikal MR. Low intake valve lift in a port fuel-injected engine. *Energy* 2009;34(12):2042–50.
- [86] Koo JY, Chung HC, Shakal JS, Goto S. Characteristics of a liquefied butane spray. *KSME Int J* 1998;12:112–22.
- [87] Payri R, Tormos B, Salvador FJ, Araneo L. Spray droplet and velocity characterization for convergent nozzles with three different diameters. *Fuel* 2008;87:3176–82.